The Pennsylvania State University

The Graduate School

Department of Civil Engineering

A COMPARATIVE ANALYSIS OF CONCRETE FORMWORK PRODUCTIVITY INFLUENCE FACTORS

A Thesis in

Civil Engineering

by

James D. Shumway IV

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

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ABSTRACT

Concrete formwork labor costs constitute over 1/3 of total concrete construction costs. The factors which most influence formwork productivity must be identified and their impact quantified to improve productivity and provide accurate forecasting. Productivity was defined as workhours per 100 square feet of form area in contact with concrete. The thesis scope was limited to wall and column formwork.

An extensive literature search found factors which significantly impact productivity to include repetition, weather events, sequencing, and material mangement. A productivity influence factor [PIF] was defined as the productivity rate impacted by a specific factor divided by the non-impacted rate. A comprehensive quantitative list of influencing factors was compiled.

Four local projects were studied to compare the influence of various factors. Data collection methods were adapted from a recent productivity data collection manual [PDCM]. Improvements to PDCM procedures were suggested.

Data from the projects were analyzed and compared to PIF values from other sources. Several factors were within 10% of the literature values, while others varied widely based on the impacted area. New factors such as footing elevation changes and piecework were identified.

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Chapter 1

INTRODUCTION

Identification of factors which can reduce the number of labor hours required to erect, align and strip concrete formwork will help to improve the cost effectiveness of construction operations. Formwork labor expenses constitute nearly 35% of the total cost of vertical concrete work (Adrian 1975a, p.1). To maintain labor cost at a minimum, management must optimize conditions at the site by focusing on factors which will improve labor productivity.

Repetitive design dimensions, proper system selection, efficient scheduling, and careful activity coordination can yield significant productivity savings. However, inadequate material availability, rework, improper sequencing, and disruptions are among previously identified causes which can contribute to poor formwork productivity (Thomas and Smith 1990). Improving formwork construction efficiency requires identification and quantification of the factors which can be shown to impact the formwork crew's productivity.

1.1 Background

Productivity improvement techniques are based on qualitative and quantitative data collected at a project site. This information can then be analyzed to identify trends, evaluate causes of productivity fluctuations, and measure improvement program effectiveness (Business Roundtable 1985, p.1). However, productivity information collection systems vary among the work reported by various researchers. The data collection system for this thesis is based on a data collection technique developed by Thomas and Kramer (1987) for the Construction Industry Institute. This method has been used successfully on projects worldwide with consistent results (Bilal and Thomas 1990).

Using this technique, productivity is defined as labor input divided by work output over a finite time interval (Thomas and Kramer 1987, p.3). For example, if a crew required 12 work hours to install 100 square feet of completed concrete forms, the productivity rate would be 12 work-hours per 100 square feet of contact area (SFCA). This study adopts the 100 SFCA standard used by Adrian (1975b) and other sources versus a one SFCA standard for reporting productivity values related to form surface contact area.

Specific productivity measurement methods have been proposed by Thomas, Smith and Horner in the Procedures Manual for Collecting Productivity and Related Data of Labor-Intensive Activities on Commercial Construction Projects: Concrete Formwork (1991). This Productivity Data Collection Manual, or PDCM, provides instructions for standard data collection procedures and identifies common terminology for studying formwork productivity. While a similar data collection methodology was validated for masonry work (Sanders 1988), the revised 1991 PDCM procedures have not been validated for formwork.

Researchers have identified a number of significant factors which impact formwork productivity. Some studies have focused on management and design factors such as constructability and repetition (Qabbani 1987 and Touran 1988). Bennett (1990, pg. 67) concentrated on environmental factors such as weather and disruptions. Estimating manuals provide data on some specific formwork system impacts (Means 1986 and Richardson Engineering Services 1989). However, the influence to productivity from factors such as corners, bulkhead placement, formwork penetrations, and other system interferences have not been thoroughly evaluated.

1.2 Problem Statement

Data collection procedures should support factor identification and evaluation, but remain flexible enough to identify new factors. Information obtained from data analysis should focus on major influences to avoid adding irrelevant details to future data collection schemes.

No single reference contains a comprehensive list of quantitative formwork system factors. Consolidation of such factors will assist productivity forecast modeling efforts and provide an extensive view of productivity disruptions. Many inconsistencies which exist between sources may be rectified with a consistent measurement standard.

1.3 Objectives and Scope

The objectives of the thesis follow.

(1) Identify the factors from the literature which are thought to influence formwork system productivity and evaluate their contribution. Compile a comprehensive list of factors, their quantitative impact, and the sources.

(2) Field test the Concrete Formwork Productivity Data Collection Manual [PDCM] (1991) procedures on local projects. Recommend improvements to PDCM procedures.

(3) Analyze and compare factor values from other sources with local project data collected using the PDCM.

The scope was limited to cast-in-place vertical concrete formwork less than 35 feet in total height. Formwork systems included in the study were primarily modular hand-set and ganged modular panel systems.

1.4 Methodology

The objectives of this thesis were accomplished with a combination of research methods.

Database searches of the National Technical Information Service (NTIS); Knowledge Index - COMPENDEX (Engineering Index); and University Microfilms International (Dissertations) yielded few journal articles and papers related to the subject. Bibliographies and various agency libraries offered a few reports. The literature research included reviewing estimating manuals (Means 1986 and

Richardson Engineering Services 1989); research reports (Qabbani 1987); and literature provided by manufacturers of forms (Economy Forms 1975 and Symons Corporation 1986).

Productivity data reported by the various sources often used different definitions of productivity or efficiency. Data from these references were converted to workhours per 100 SFCA. The author developed a productivity influence factor [PIF] to calculate quantitative factor impacts. The PIF was defined as the impacted rate divided by the non-impacted rate. The PIF easily converted base productivity rates to impacted rates when weather conditions, management factors, or disruptions dictated.

The data used in this thesis were collected from four projects in central Pennsylvania between April and October 1991. The projects included a composting facility, a wastewater tertiary filter building, an extension to an art museum, and a three-level parking deck. Daily visits were made to each site. Photos, notes and sketches accompanied the numerical data collected in the PDCM format.

A rules of credit technique was used to convert field data to a standard measure of productivity for each working day. Rules of credit procedures are described in Chapter 3.

Raw data were stored in a database of LOTUS 1-2-3 spreadsheet files and evaluated using STATGRAPHICS (Version 5.0). Analysis of variance and multiple regression were utilized to evaluate the data.

1.5 Organization of the Thesis

Chapter 2 reviews applicable literature and summarizes the factors identified by other sources.

Chapter 3 focuses on modifications made to the data collection method. Chapter 3 also provides background information on the projects from which data was collected.

Chapter 4 presents the analysis of project data based on various general and system factor effects.

Chapter 5 compares the results of this study to data reported in the literature sources.

Chapter 6 summarizes the findings of this study and outlines recommendations for future work.

1.6 Glossary of Terms

Blockout - An insert set within formwork to create a haunch, column bench, or other concrete surface feature.

Boxout - An insert which forms a window, door, or other opening through the finished concrete structure.

Braces - Members which hold formwork in place, bracing the wales and strongbacks against lateral concrete pressure.

Bulkhead - A special form placed to close off a form to create a joint or termination.

Disruptions - Causative events or factors which impede productivity, like interruptions and work stoppages.

Gangforms - Multiple sections of modular form panels joined together. Usually bracing elements remain attached.

Learning Curve - The idea that workhours expended on an activity are reduced through repetition or practice.

Penetrations - Similar to boxouts, except that the penetrating elements, such as pipesleeves, rebar or conduit remain in the concrete after placement.

Productivity Influence Factor - A conversion factor defined as the impacted rate divided by the non-impacted rate. These factors show the quantitative influence of rain, repetition, rework, or other causes.

Spreaders and Ties - Formwork components which hold the two walls together and retain proper spacing.

Strongbacks - Vertical supports for ganged panels.

Wales - Horizontal supports which brace gangforms. Also called "walers."

Chapter 2

LITERATURE REVIEW

Dozens of factors can contribute to poor productivity on vertical formwork. This chapter focuses on the most significant factors identified through research, and estimates their quantitative impact through the use of a standard productivity influence factor.

2.1 Background

Thomas and Smith's Loss of Construction Labor Productivity Due to Inefficiences and Disruptions presented the most complete summary of studied factors. The report identified primary, root, and indirect causes of losses in productivity (Thomas and Smith 1990, pg. 4). Many of these causes can be genericly discussed for various construction activities. Primary causes cited by the report included: weather events, poor sequencing, interruptions, congestion, rework and restricted access. Root causes were defined as: crew size, poor supervision, material or tool availability, artificial restraints, and constructability. Overtime, shift work, turnover, absenteeism, and change orders were among the specified indirect causes. Some of the factors have been examined in detail, while others have scarcely been probed.

2.2 Productivity Influence Factor

Various sources described productivity factor impacts as disruption indices, relative efficiency, or productivity loss percentages. Some sources defined productivity by output (SFCA or square meters) per workhour. Others used the accepted definition of workhours per 100 SFCA.

Efficiency was alternatively related as a ratio of impacted daily output to normal daily output, or the ratio of normal daily productivity to impacted daily productivity. For example, Clapp's study, cited by Thomas and Smith (1990, pp. 76-78) indicated that in "very bad" weather crews which normally took 10 hours to complete a specified quantity of work, required 19.6 hours to achieve the same output. The weather event impacted efficiency rate was about 50% [10/19.6 = 51%] (Thomas and Smith 1990, pg. 77).

The varying definitions were confusing and made comparisons difficult to understand. To obtain a consistent definition throughout this thesis, all cited productivity impacts were converted to a productivity influence factor or PIF. The PIF measures the ratio of the disrupted or improved productivity rate to the base or undisrupted productivity rate. So, for the example from Clapp's study, the PIF was 1.96 [19.6/10]. Note that a higher PIF indicates worse productivity, while a PIF of less than 1 means improvement occured. Given base rates, the PIF permits simple calculation of impacted productivity rates.

2.3 Learning Curve and Repetition

Although some dispute learning curve effects, several studies show greater formwork efficiency occured with repetition of similar structural elements (Burkhart et al. 1987 and Touran 1988). Improvement was most evident on projects where highly repetitive components were used, such as a multi-story office building with identical floor plans. Wide variation in dimensions and intricate architectural patterns reduced the noted improvement. Complicated bulkheads, inserts, and custom forms slowed the progress associated with the learning curve (Qabbani 1987, pg. 56).

Some improvement associated with the learning curve results from using ganged panels or hardware. This advantage diminishes when panels are frequently dismantled and reconfigured. This is closely related to system factors discussed later in this thesis.

Qabbani studied the use of repetitive formwork on a 17 story Seattle building. He found an improvement through repetition for the upper eight floors of 17-24% over the base productivity rate (Burkhart, Touran and Qabbani 1987, pg. 853). The average productivity influence factor can be calculated as 0.80.

2.4 Disruptions and Environmental Factors

Disruptions may stem from weather events, labor problems, material shortages, poor coordination with associated trades, and other causes. After a disruption occurs, remobilization, personnel reorientation, changes in organization, or different site conditions can drastically reduce productivity. Frantazolas' study (1984, C.2.2) found that the disruption of a six week strike resulted in a productivity influence factor of 1.72.

Bennett (1990, pg. 67) and other research (Thomas and Smith 1990, pp. 76-78) concluded that disruptions caused by weather events led to an average formwork productivity influence factor of 2.0. Weather related disruptions often result in a work stoppage on formwork being erected below ground level, rather than an incremental productivity loss. Residual weather impacts, such as mud, ponding, or flooding, may limit site accessibility.

The immediate impact of severe weather on productivity seems obvious, but the effects of other random disruptions are less clear. Limited data on accidents or equipment damage suggested productivity influence factors of up to 2 (Bennett 1990, pg. 67). Material supply related disruptions led to an average PIF of 4.0 (1990, pg. 67).

2.5 Management Factors

To create an environment for optimum productivity, management must understand and minimize those disruptions within their control. They can create a proper working environment by providing adequate resources, properly sequencing activities, effectively organizing the site and limiting work content changes. Improper storage and handling of concrete forms, reinforcing steel, and other materials can cause a PIF of 1.20 or more (Thomas and Smith, pg. 116). Effective sorting and distribution may avert disruptions and improve the PIF.

Bennett cited poor sequencing of preparatory footing placement and shoring removal as the cause of a productivity influence factor of 3.7 to formwork crews on selected days (1990, pg. 41). Alternatively, Proctor (1989, pg. 929) and Burkhart (1989) emphasized that proper sequencing enabled contractors to accelerate operations. On one project, which included cast-in-place columns and perimeter walls, careful equipment and crew sequencing yielded PIFs of 0.80 for the top 24 floors (Burkhart 1989, pg 77).

Personnel management practices greatly influence productivity. In one case, poor labor management and inadequate coordination with ironworkers were noted to cause disruption PIFs of 2 to 4 (Bennett 1990, pg. 42). Poor staffing practices, inadequate supervision, and crew turnover have negative, but less quantifiable productivity impacts (Thomas and Smith 1990, pp. 106-125). Adrian's overtime research documented substantial productivity losses for crews working overtime for three or more weeks (Adrian 1988, pg. 138). An estimated PIF range for overtime would vary from 1.06 to 1.67 for 45 to 77 hours per week.

2.6 Plans, Changes and Constructability

Management must ensure that work is adequately defined and understood by the workforce. Plans and specifications must be complete and accurate. Contractors must use clear, logical construction methods. Thomas and Smith (1990, pg. 104) cited information availability and degree of complex, interdependent work sequences as the major causes of poor productivity due to constructability. The estimated PIF was roughly 2-2.5, but the available data was inconclusive.

Change orders may result from project scope changes, incomplete or inaccurate design, site conditions, and other factors. Although difficult to quantify, change orders often have a serious detrimental impact on productivity. (Thomas and Smith 1990, pg. 146).

Rework may result from change orders, faulty design, poor information flow, or improper construction methods. The ensuing loss of momentum due to removing and replacing defective sections erode productivity, and can cause poor worker morale. Sanders noted a productivity loss from rework on 11 masonry projects which converted to a PIF of 2.44 (Sanders 1988).

Touran explored design and construction method impacts on formwork productivity in depth (1988, pp. 82-87). He recommended that designers use similar modules, minimize variation between structural members, and give components common dimensions for easier formwork selection. Touran raised concerns about the lack of adequate impact data resulting from formwork complexity. To develop difficulty factors for productivity forecasting, he suggested using a regression matrix. The user could then solve the matrix for unknown factors based on relative component quantities and historical productivity data for similar floors.

Table 1 summarizes the general productivity influence factors (PIF) from concrete formwork projects. While the table may not be an exhaustive list, it does represent the limits of quantified factors from the literature.

2.7 Formwork System Factors

Elements which define formwork constructability are called "system factors." These coincide with "factors that depend on the formwork requirements and geometrical shape of structural members" according to Touran (1988, pg. 82).

2.7.1 Form Type

Common materials for formwork include steel, plywood, and aluminum. Often steel frames are combined with plywood faces for economy and workability. Forms should be durable, strong, and economical. They should be easy to maneuver, assemble and strip. The form contact face material should provide a good finish, strip easily, and allow for secure installation of pipesleeves, boxouts and other hardware.

In addition to saving time, modular forms exhibit the

Table 1. Management, Site and Environmental Factors

Factor	Source	Estimated Productivity Influence Factor (PIF)
Repetition	Qabbani (1987)	PIF = 0.80
Disruptions - External		
Labor Strike	Frantazolas (1984)	PIF = 1.72
Severe Weather	Bennett (1990) Thomas/Smith (1990)	PIF = 2.0
Accidents	Bennett (1990)	PIF = 2.0
Disruptions - Internal		
Improper Sequencing	Bennett (1990)	PIF = 4.0
Material Supply/Delivery	Bennett (1990)	PIF = 4.0
Poor Contractor Coordination	Bennett (1990)	PIF = 2-4
Site Management		
Poor Material Handling	Thomas/Smith (1990)	PIF = 1.20
Effective Coordination	Burkhart (1989) Proctor (1989)	PIF = 0.80
Overtime	Adrian (1988)	PIF = 1.06 - 1.67
Rework	Sanders (1988) [Masonry only]	PIF = 2.44

NOTE: Impacted productivity rate = productivity improvement factor [PIF] x Base Rate advantages of assembly ease and higher reuse. Adrian (1989, pp. 7-9) finds productivity influence factors of 0.73 and 0.93 for aluminum forms and manufactured plywood forms compared to a base rate for steel-plywood composite forms. Aluminum forms are lightweight, so larger panels may be used in hand-setting. The plywood system offers easy hardware attachment. Steel forms are very durable, but crews often find it more difficult to attach hardware and boxouts.

Form maintenance and durability impact productivity. Forms are often damaged, patched, or modified to accept hardware. Panels seldom last their forecast lifetime. For example, steel frames with plywood face panels ideally can be used for more than 200 uses (Adrian 1989, pg. 3). However, foremen interviewed by the author on three local projects agreed that such forms must be refaced, repaired, or exchanged after only 15-30 uses.

Figure 1 illustrates the components of a common steel frame and plywood modular form panel.

2.7.2 Panel Size

Panel sizes are selected based on system availability, compatibility, and component design dimensions. Intuitively, it is expected that greater efficiency can be achieved with fewer, larger panels. However, this concept is bounded by the shapes, heights, lengths, and component features of the design. Material handling equipment,

Modular Form Components

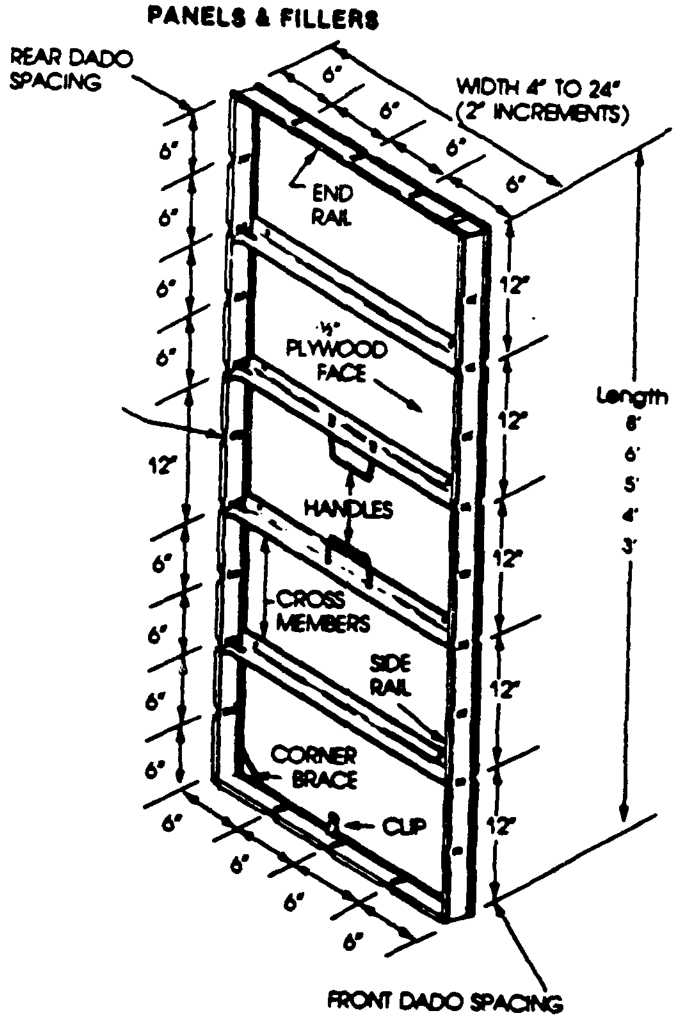

Figure 1. Modular Form Components

Source: Steel Ply Application Guide 1986 available form systems, crew characteristics, and placement method will also influence size seiection. No source provides adequate data to calculate a PIF for panel size.

2.7.3 Formed Surface Shape

Curved or irregular surface shapes require more effort than straight vertical face walls. Even fairly simple circular shapes result in productivity influence factors ranging from 1.5 to 2 when compared to an equivalent amount of straight wall SFCA (Richardson 1989, pg. 3-11-2).

2.7.4 Form Height

Wall or column height, slab or beam intersections, and available form sizes are some of the features which impact form height. Forms are typically 6 inches higher than the finished wall or column. Panel height greater than 6 inches above the concrete surface may interfere with access for concrete finishing or installing boxouts for ledges or column benches.

When wall heights exceed 8′, form design requires additional bracing and crews often work from scaffolding which may also be attached to the formwork. The extra erection work, impaired crew mobility, and reduced access to materials and equipment reduce productivity. PIF values for higher walls [over 8′] range from 1.15 to 1.30 compared to base rates for low walls [under 8′] (Peurifoy and Oberlender

1989, pg. 151, and Richardson 1989, pg. 3-10-15). For steel framed plywood formwork, the estimated PIF compared to the base rate for walls under 8′ high is 1.26 for 8-16′ high walls, and 1.43 for 16-20′ high walls (Means 1986, pg. 72).

2.7.5 Formwork Placement Location

Bennett (1990) and Qabbani (1987) cited the influence of location, which appears to combine difficult access for equipment or personnel, and other complexity factors like corners and corbels. The estimated PIF range is 1.4 to 4 for formwork location. Due to limited data and the wide range for interpretation, the factor impact is inconclusive.

2.7.6 Method of Assembly and Placement

Generally, avoiding the use of custom built forms and maximizing the use of modular gang-forms will effectively increase productivity. Figure 2 illustrates gang form components. Compared to modular steel-plywood forms, plywood job-built forms translate to a PIF of 2.33, for similarly skilled crews to assemble and erect (Adrian 1989, pg. 9). Gang forming improves productivity with a PIF of 0.80-0.90 (Means 1986, pg. 71). A recent formwork productivity study found a PIF for gang forming of 0.79 (Bennett 1990, pg. 60). If substantial reconfiguration of gang forms is necessary or proper equipment is unavailable, the advantage may be lost.

Gang Form Components

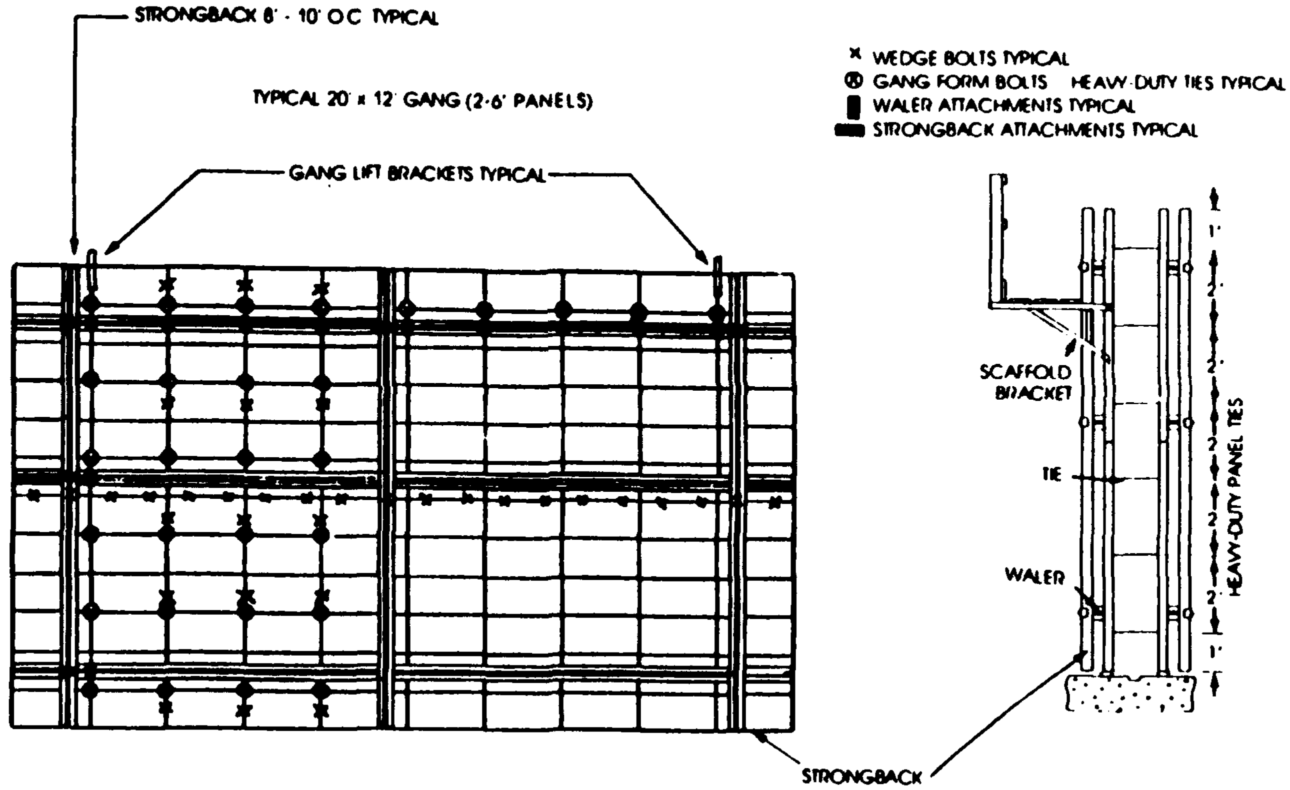

Figure 2. Gang Form Components

Source: Steel Ply Application Guide 1986

2.7.7 Multiple Modular Form Usage

Means (1986, pg. 72) suggested a PIF of 0.85 to 0.90 when modular forms are used 4 times per month versus one use. The major influencing factor in this case appears to be repetition, so use of this PIF would be redundant.

2.7.8 Bracing

For gang forming, installing and removing pipe braces accounts for 8-10% of the total workhours involved in the base productivity rate, not including strongback or wale installation (Economy Forms Corporation Rate Sheets 1975).

2.7.9 Connections

Manufacturers of the different modular forming systems use various connection systems to secure panels together. Wedge pins (Symons), clips (Simplex), and dowels are some of the hardware systems used. Most systems are intended to be strong, simply maintained, and quickly erected. The connection systems of modular forms are a major contributor to their productivity advantage and the ability to gang-form easily. The connection systems distinguish one system from another. Including panel connections, ties, and spreaders, 30-40% of install and strip times are devoted to connecting hardware for gang forms (EFCO Rate Sheets 1975). For hand-set forming, the rate might reach 50%, since each individual panel must be connected. Tie installation alone accounts for approximately 10% of form erection time (EFCO Rate Sheets 1975). No definitive PIF comparisons between different styles of hardware were found in the literature.

2.7.10 Bulkheads

Bulkheads are special forms constructed to form a joint or termination. Unless the formwork is joining two previously poured sections, most wall sections will require at least one bulkhead. Wall thickness and height determine bulkhead dimensions. If the bulkhead dimensions frequently change or the penetrations due to rebar patterns are complex, the PIF will increase.

Qabbani's data showed a bulkhead PIF of 3.8 compared to the base productivity rate for beam forms (1987, pg. 67b). Based on the bulkhead type and wall thickness, Richardson's (1989, pg. 3-10-19) suggested a bulkhead PIF range of 1.35-4.8 times the base rate.

This PIF is based only on the installed bulkhead area [SFCA]. Like boxouts and other system factors, bulkheads have specific dimensions and present varying levels of difficulty. Therefore, the PIF presented in literature represents the range of impacts for a specific area, not the total daily output. EFCO "Rate Sheets" indicated that bulkhead setting workhours constituted 8-17% of the total wall form erection times. Corresponding bulkhead quantities averaged only 5-10 SFCA per 100 SFCA of installed wall formwork. Thus, the overall average bulkhead PIF would range from 1.07 to 1.48 [1 [base rate] + 0.05 [bulkhead SFCA/total daily SFCA] x 1.35 = 1.07 and 1 + 0.10 x 4.8 = 1.48]. One innovative solution which may reduce the PIF up to 50% is the use of remain-in-place precast concrete bulkheads (Burkhart 1989, pg. 65).

2.7.11 Boxouts and Penetrations

Boxouts are needed whenever doors, windows or other cavities must be formed through a wall. Penetrations occur when pipes, conduit, or rebar for a connecting wall must penetrate a wall form. One to four small penetrations [less than 6 inches in diameter], probably do not greatly impact productivity and could be ignored. However, a large quantity of rebar penetrations may require a custom drilled rebar template form. Pipe sleeves must be precisely located and attached to the form. The estimated productivity influence factor for boxouts and large penetrations is 1.5 times the wall thickness in feet for the area occupied by the boxout form [SFCA] over the base productivity rate (Richardson 1989, pg. 3-10-21). This labor time is in addition to the effort required to provide wall forms on each side of the boxout. For example, a 5' wide by 5' high boxout penetrating through a 16 inch thick wall translates to a PIF of 2 [16/12 x 1.5 = 2] for the impacted 25 square feet of wall area. If the daily output was 100 SFCA, the overall PIF would be 1.5 [1 [base rate] + 0.25 [25 SFCA/100 SFCA] x 2 = 1.5]. The range of overall PIFs for boxouts could range from 1.1 to 2 or greater, depending on complexity, dimensions, and daily output.

2.7.12 Corners and Intersections

Wall intersections require the use of smaller corner forms and usually involve significantly more effort to form than straight runs. There are two types of corners, inside and outside. These are used as displayed in Figure 3 to form "T" , cross-wall, two and four corner intersections.

Richardson's (1989, pp. 3-10-17 and -18) suggests a range of PIFs based on intersection type, from 1 to 4.5 times the intersection height and number of corners. Qabbani (1987, pg. 67b) found beam/slab intersection PIFs to range up to 5 times the standard rate. Using Richardson's method, a 16.5 feet high intersection with one inside and one outside corner would take 0.99 times the base workhours required for 100 SFCA [3 [PIF] x 2 [number of corners] x 16.5/100 = 0.99]. This must be added to the base rate for the forms themselves. If the daily output in this example were 100 SFCA, the PIF caused by corners would be 1.99. If the output were 500 SFCA, the PIF would be 1.2 [1 + 0.99/ [500/100]]. The overall corner PIF could range from just over 1 to 2, depending on complexity, height, and daily output.

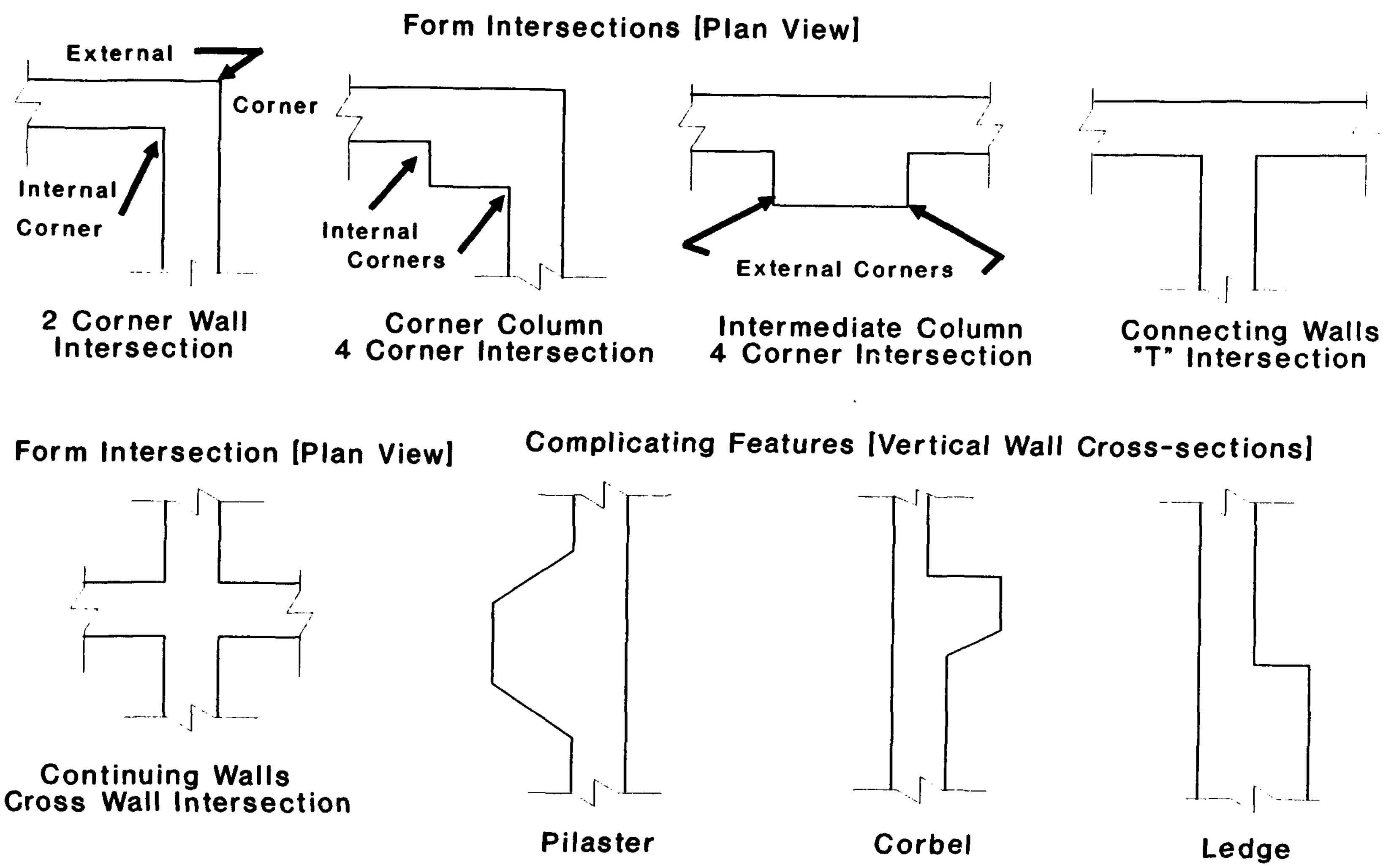

Figure 3. Corners, Intersections, and Complicating Features

Vertical corners may result from footing elevation changes, outer elevated curbs, or intersections with slabs. No PIF values were found in the literature for vertical corners or elevation changes.

2.7.13 Pilasters and Other Design Details

Walls often require structural or architectural details such as pilasters, ledges, haunches or corbels to support beams or columns. A few of these were displayed in Figure 3. Details are usually formed using custom built blockouts, form inserts, or filler forms with special angles, shapes and dimensions. The extra effort to form these details for the wall area occupied by the feature [SFCA] ranges from 2 to 5 times the base productivity rate for the impacted length or area (Richardson 1989, pp. 3-10-19 to 3-10-25 and Means 1986, pg. 72).

The PIF for pilasters is calculated by multiplying the lineal feet of pilaster by 0.05 [5/100 SFCA]. For example, the PIF for a 24' long pilaster would be 1.2 [24 x 0.05]. If this pilaster were constructed on a day when 500 SFCA of forms were erected, the overall PIF would be 1.24 [1 + 1.2/ [500/100]]. A 2' high by 38' long corbel would add a PIF of 1.75 to the base rate [2 x 38 x 2.3/100]. On a day when 500 SFCA were erected, the net overall PIF would be 1.35 [1 + 1.75/[500/100]]. The potential range for design details ranges from 1.1 to over 2 based on output and complexity.

These PIFs are based on a single form use, and lower factors may be used for 2 or more uses. The PIF may be reduced from 10% for 2 uses up to 20% for 4 uses.

2.8 Summary of Formwork System Factors

Formwork system related factors can significantly impact productivity rates for vertical concrete forming. Table 2 summarizes system factors identified in the literature. Factors such as corners, bulkheads, corbels, and boxouts require definition of the occupied wall area, or impacted length. PIFs from the literature must be converted to account for the occupied area versus daily output and the complexity and dimensions of the particular bulkhead or boxout. This makes them difficult to compare with wall height or gang forming PIFs for example.

Analysis using a single factor without considering overall project conditions may lead to overestimating that factor's importance. For instance, simply looking at overtime without considering height, bulkheads, and weather impacts would inflate the calculated productivity influence factor. The interrelationships between various system and general factors need to be explored further. To improve productivity, project managers and designers should increase standardization, repetition, and uniform shapes. They must also reduce the potential for internal disruptions and prepare to minimize the impact of external disruptions.

Table 2. Formwork System Productivity Factors

Factor	Source	Estimated Productivity Influence Factor (PIF)
Material	Adrian (1989)	
Steel-plywood		Base Rate
Aluminum		PIF = 0.73
Plywood		PIF = 0.93
Shape	Richardson (1989)	
Straight	and Means (1986)	Base Rate
Curved		PIF = 1.5 - 2.0
Height	Richardson (1989),	
to 8' high	Peurifoy (1989),	Base Rate
8' to 16'	and Means (1986)	PIF = 1.15 - 1.26
16' to 24'		PIF = 1.30 - 1.43
Location	Bennett (1990) and	
Interior/Ext.	Qabbani (1987)	PIF = 1.4 - 4
Placement	Richardson (1989),	
Method	Means (1986), and	
Modular	Adrian (1975/1989)	Base Rate
Ganged	Bennett (1990)	PIF = 0.79 - 0.90
Job-built		PIF = 2.33
Modular form		
Reuse	Means (1986)	PIF = 0.85 - 0.90

Additive Factors Based on Occupied Area or Impacted Length
[Net PIF = 1 + [PIF x occupied area/daily output]].

Bulkheads	Qabbani/Richardson	PIF = 1.35 - 4.80
[Multiply by area]		Net PIF = 1.1 - 1.5
Boxouts	Richardson (1989)	PIF = 1.5 - 2.5
[Multiply by occupied area]		Net PIF = 1.1 - 2+
Corners	Richardson (1989)	PIF = 1 to 4.5
[Length]	Qabbani (1987)	Net PIF = 1.1 - 2
Design Details	Means (1986) and	
Pilasters	Richardson (1989)	PIF = 0.5 x Length
[Length]		Net PIF = 1.1 - 2+
Haunches	Means (1986) and	PIF = 2.6 x Area
Corbels	Richardson (1989)	PIF = 2.3 - 3.0
Ledges		PIF = 2.0
[Area]		Net PIF = 1.1 - 2+

Chapter 3

PROJECT DATA COLLECTION PROCEDURES

Much of the data collected during previous formwork productivity studies failed to provide all the information required to fully understand the factors affecting productivity. Based on the Formwork Productivity Data Collection Manual [PDCM] (Thomas et al. 1991), data was collected on four projects in the State College, Pennsylvania area. The data collection focused on vertical formwork comprised of foundation, first and second level walls. A sample set of the data collection forms are provided in Appendix A.

3.1 Data Collection Method Overview

The data collection methodology required daily site visits to collect data covering nine topic areas. The bulk of the daily data included workhours devoted to studied activities and in-place formwork quantities erected, braced, aligned, or stripped. The procedures manual required information on: weather, site layout/conditions, management practices, construction method, and project organization.

For this study, design features and work content were of particular interest. The data was collected as prescribed in the procedures manual, but with special emphasis toward specific system factors. These factors included: form type, panel size, formwork height, placement method, corners due to footing elevation changes, interior/ exterior form corners, connections, bulkheads, boxouts, pipesleeves, pilasters, corbels, ledges, and bearing seats.

Daily workhours were reported by the foreman and verified by the project manager or superintendent. Some contractors were reluctant to show written payroll records or cost data, but they would report workhours orally. They regarded the written records as proprietary information. Total forming hours were adjusted by subtracting hours spent placing concrete. On two projects, the formwork crew also erected rebar and constructed footings, so these hours also had to be subtracted from the total.

Careful records of output quantities were kept. Actual square feet of contact area (SFCA) came from construction drawings, on-site measurements and observed quantities. The ratio of square feet in contact with concrete [SFCA] to erected panel surface area in square feet was always less than 1, because concrete was not poured to the top of each form. For example, a wall 17'-4" high might be formed using three 6' high panels. The effective height for calculating SFCA is 17'-4", not 18' [3 x 6']. Therefore, the panels cannot be simply counted and multiplied by their surface area to obtain SFCA. This varies from Bennett's accounting procedures (1990), but the method provides a more realistic quantity measurement from which analysis can be performed.

The current data collection system incorporates some of the system factors mentioned previously and several others. These include: construction method, work type, panel size, wall thickness, bearing seats, sloping walls, tie patterns, form liners, rustication strips, interior/exterior corners, and boxouts (SFCA).

The manual suggests tracking bulkhead construction as a separate activity. Nevertheless, the contractors on these projects did not provide specific workhour breakdowns for bulkheads, boxouts, or other system factors. Effort expended to install these features was included in daily workhours used to calculate daily and cumulative productivity. However, the PDCM rules of credit, described in the next section, do not account for bulkhead, boxout, and blockout square feet of contact area. The quantities were tracked separately and not added to daily output.

Disruptions and observed inefficiencies, which could potentially skew the data, were noted. These included: weather conditions causing a delay or work stoppage, conflicting priorities, labor diverted to other activities, absence of ironworkers, or pipesleeve layout problems.

3.2 Rules of Credit

Rules of credit recognize the contribution of partially completed work for accurate work output measurement. Rules of credit are based on required effort and vary with the type of work. For example, the first side of a wall form usually requires more effort to erect than the second side. Using rules of credit, forms erected in one section and forms stripped in another area on the same workday can be combined into an equivalent completed wall form quantity. The rules of credit shown in Table 3 were derived from previous studies and estimating manuals for the Productivity Data Collection Manual (Thomas et al. 1991, pp. 60-61).

The rules of credit listed in the PDCM Appendix (pp. 60-61) were reversed. The gang form rules of credit were listed as the modular form rules of credit and vice versa. The error in data analysis was noted when reviewing rules of credit used by Bennett for gang forming (1990, pg. 20).

After consideration, all project data were reevaluated using the actual modular form rules of credit. Two projects used only hand-set modular forms. Two others used gang forms for 30-60% of the surface area. However, modular forms were widely used on these projects for corners, columns, lower and shorter wall sections, and around blockouts. Ganged sections on both were removed and reconfigured frequently. The modular form rules of credit were more flexible for allocating bracing and alignment credit. They also correlate better to the estimated times for gang form bracing and alignment given by Richardson (1989, pg. 3-10-2). Therefore, the modular form rules of credit shown in Table 3 were used throughout data analysis.

Table 3. Rules of Credit for Formwork

For Walls:

Subtask	Description	Modular form Weight
Erect first side of wall	Place and attach panels.	0.60
Erect opposite side	Place and attach panels.	0.40
Brace wall	Install all wales, strongbacks, and rakers. (If already attached, give credit at the time of erection).	0.20
Align forms	Install tie rods, plumb and level, and adjust to prepare for concrete placement (pour).	0.20
Strip forms	Remove formwork. (Ignore cleaning and oiling).	0.10

For Columns or Piers:

Subtask	Desription	Weight
Erect first three sides	Placement and securing of panels.	0.75
Erect fourth side	Check and align rebar, place and attach panels for side.	0.35
Brace and final alignment	Install braces, clamps, and connections to secure formwork, adjust and prepare for pouring.	0.30
Strip forms	Remove formwork from all four sides (ignore cleaning and oiling).	0.05

Source: Formwork Productivity Data Collection Manual [PDCM] (1991 pages 60-61).

3.3 General Project Information

All four projects were constructed by general or specialty contractors using non-union workforces for public owners. Table 4 summarizes important project data.

3.4 Project #1: Tertiary Filter Building

This project was a 2 level reinforced concrete structure and is illustrated in Figures 3 and 4. The general contractor's crew erected formwork, poured concrete, stripped panels, and maintained the forms. All forms were owned by the general contractor. A subcontractor installed the extensive reinforcing steel.

The first level consisted of 11'6" high foundation walls separated into two sections by an L-shaped wall. These below ground-level walls were formed over a 5 week period in April and May. The crew used 6' by 12' all-steel panels to build 12' by 12' ganged sections, which were supplemented with modular panels.

The second level consisted of 16'6" to 19'6" high exterior walls and 7'6" high baffle walls. It was built over a 9 week period through July and August. Various size modular steel framed plywood panels were handset or ganged.

The work on both levels was complex with 26 large diameter (18" to 42") pipesleeves, 41 corners, 11 bulkheads, and 12 boxouts. Delays were attributed to pipesleeve layout, complex boxouts, labor delays, and thunderstorms.

Table 4. Project Summary Statistics

	PROJECTS #1 Tertiary Filter	#2 Compost Facility	#3 Art Museum	#4 Parking Deck
Levels	2	1	1	2
Wall Height (ft)	11.5 - 19.5	7.5	4.5 - 17.7	6.5 - 26
Wall Thickness (inches)	10 - 16	6	8 - 24	8 - 16
Areas (square ft.):				
Plan Area	3,240	20,350	11,330	18,600
Site Area	4,800	30,000+	36,800	23,430
Vertical SFCA	18,768	46,200	13,400	12,800
Number of:				
Bulkheads	10	95	10	15
Corners	41	0	44	30
Elev. Changes	4	0	6	3
Blockouts	8	0	45	**
Boxouts	12	0	6	0
Penetrations	26	0	6	0
Method	Ganged	Hand-set	Hand-set	Ganged
% Ganged (Avg.)	44%	0	0	30%
Type	Steel/SPF	SPF	SPF	Steel
Ownership	Owned	Leased	Leased	Owned
Contractor	General	General	Specialty	General
Type	Non-Union	Non-Union	Non-union	Non-union
Crew Size (Avg.)	8	15	4	12
Workdays Observed	68	23	43	40
Cumulative Productivity (WH/100 SFCA)	20 (1st Level) 15 (2nd Level)	5.5	6.4	14.9

SPF - Steel framed, plywood faced panels [most common type].

** Full length corbel blockouts and angled walls.

Tertiary Filter Building, 1st Level

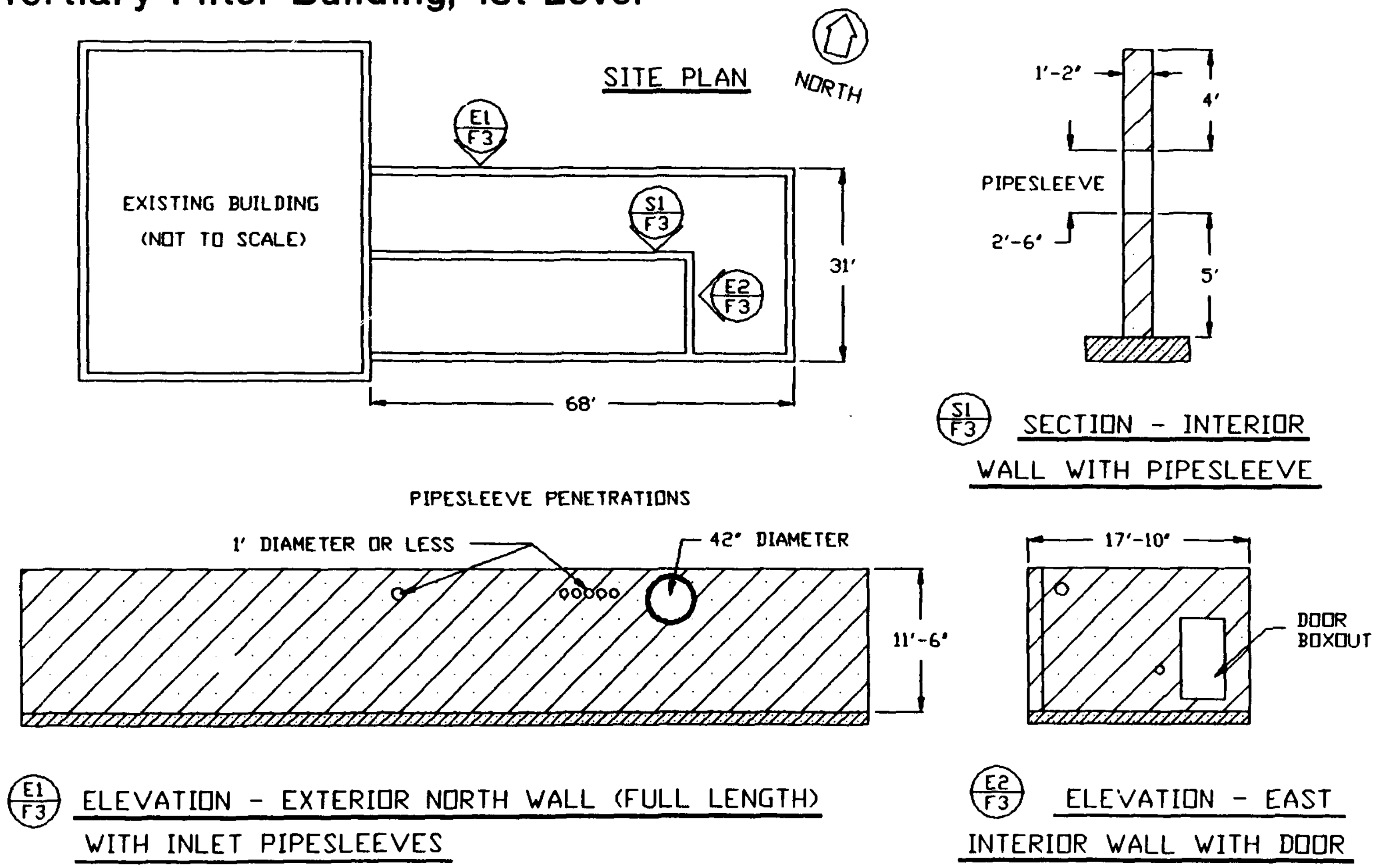

Figure 4. Tertiary Filter Building, 1st Level Views

Tertiary Filter Building, 2nd Level

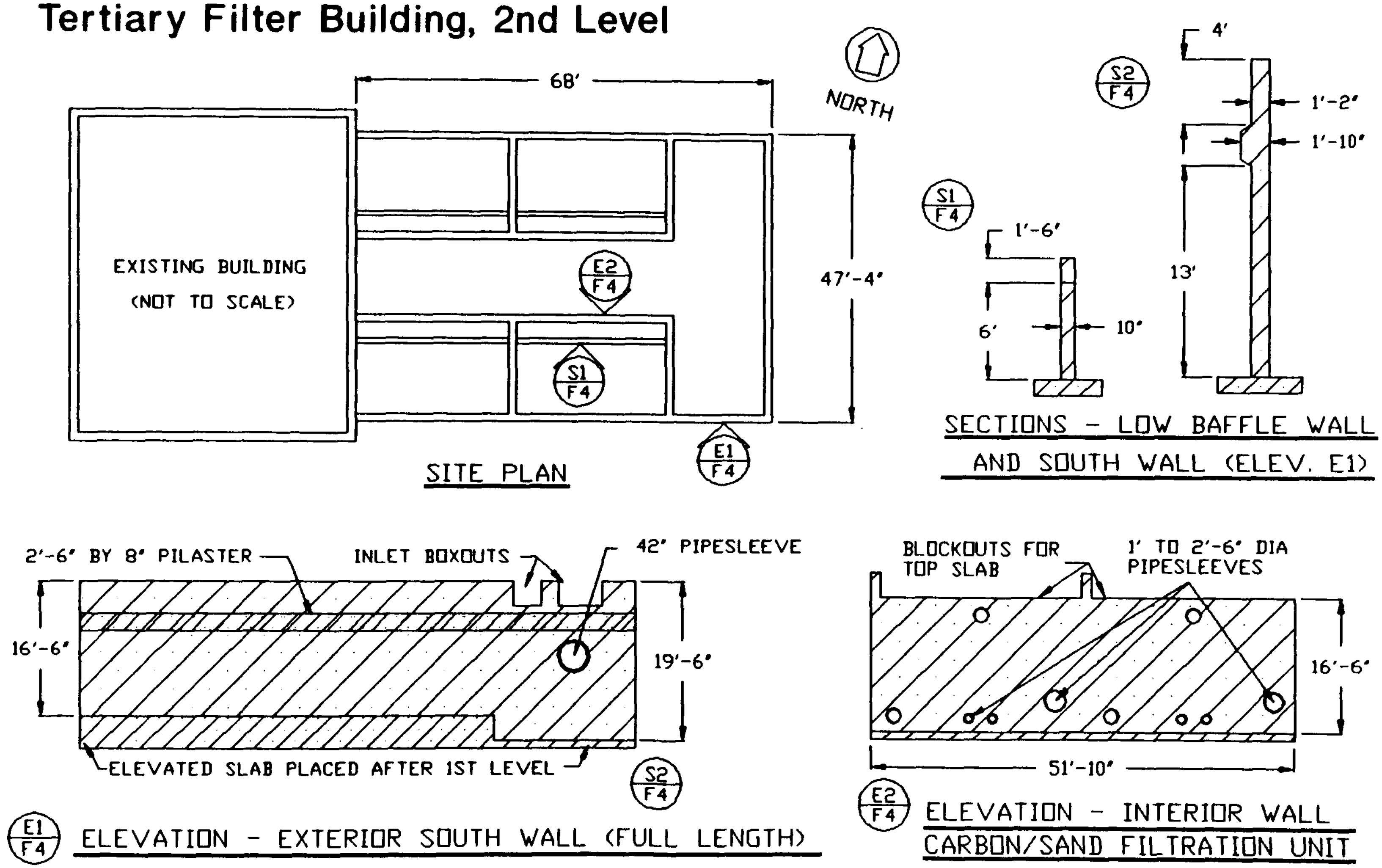

Figure 5. Tertiary Filter Building, 2nd Level Views

3.5 Project #2: Composting Facility

The main concrete components of the compost facility were 15 parallel walls. Figure 5 shows typical section, elevation and plan views. The general contractor supervised three crews erecting formwork and a separate crew which stripped and cleaned panels. A subcontractor erected rebar.

Each 7'6" high wall was 208 feet long and they were erected in three groups of five. Construction began in mid-April and finished in mid-May. Each wall group required 2-3 days to erect, pour, and strip. The forms were primarily 2' by 8' steel framed plywood modular forms leased by the general contractor. Major system impacts were the large number of bulkheads and 1' high steps formed at the base of the exterior walls of each group. A custom plywood form and three small panels were used to form the step configuration.

Rain delays slowed productivity.

3.6 Project #3: Art Museum Wing Expansion

The cast-in-place foundation walls and columns shown in Figure 6 were studied on this project. The small specialty contractor crew included a working foreman. They placed rebar, constructed footings, poured concrete, and hand-set the forms. The majority of the work was accomplished between late June and early September. Modular steel framed plywood forms were leased for the project.

The walls were 4'6" to 17'8" high and included numerous

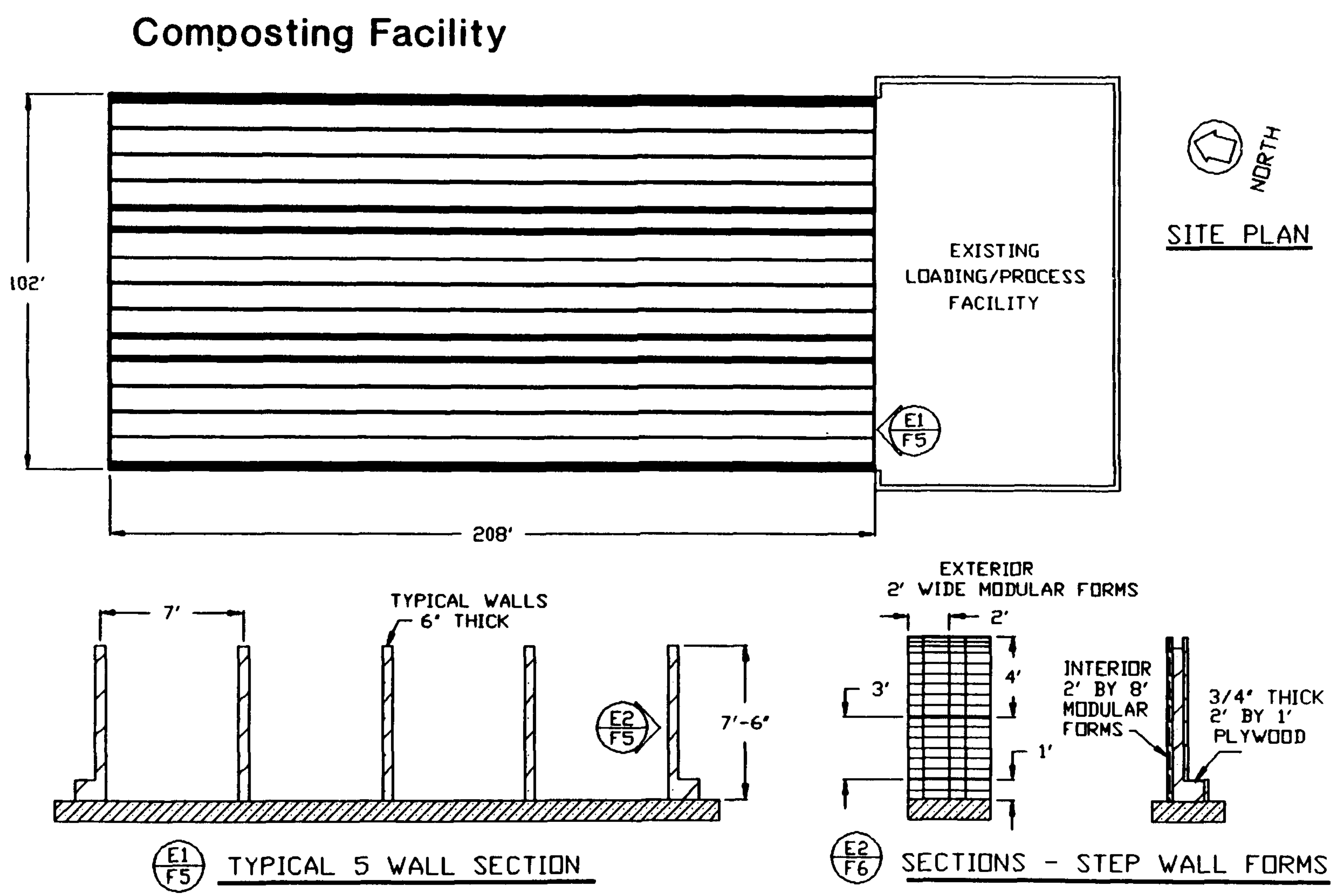

Figure 6. Composting Facility Plan and Views

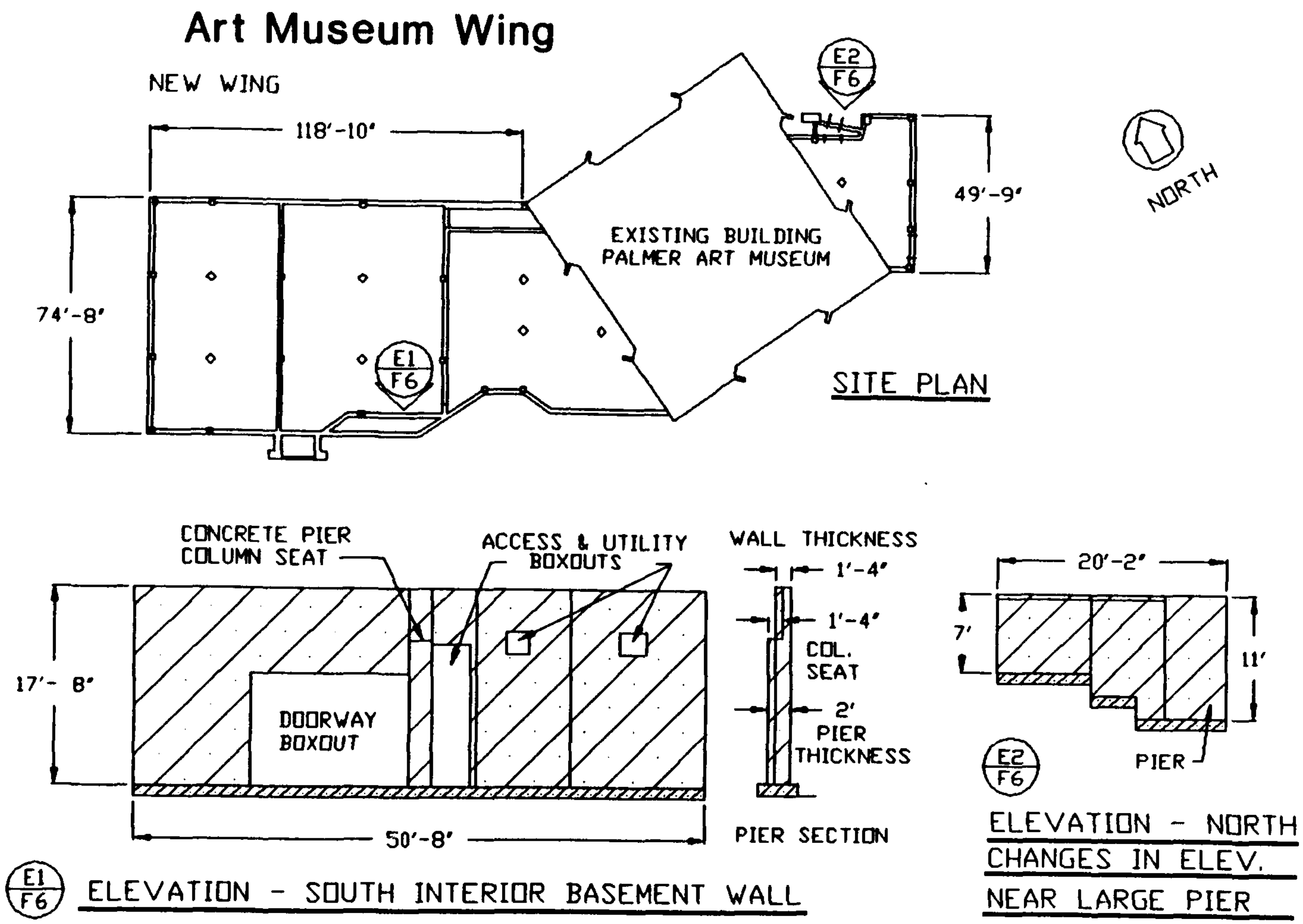

Figure 7. Art Museum Wing Plan and Views

corners and adjoining columns. Other system factors noted were individual piers, variable footing levels, and large boxouts. Rain and diversion of crew members to other activities hindered overall labor productivity.

3.7 Project #4: Parking Deck

This project was built on a congested site between existing buildings. The scope of work studied included piers, the stairwell foundation, cast-in-place walls, and columns for the 3 level parking deck shown in Figure 7. The general contractor's crew placed rebar, constructed footings, and erected hand-set and gang forms. The forms were primarily 2' by 4' EFCO all-steel panels owned by the general contractor. Work commenced in late August and continued through late October.

Panels were ganged together for large sections. The forms were handset for short sections, columns, blockouts, and above gang forms on high sections. The 22'-26' high walls and adjoining columns were formed in two lifts. System factors included: corbel blockouts to support precast elements, sloping walls for ramps, and corners. Rain, overtime, poor sequencing and inadequate staffing caused delays and reduced productivity.

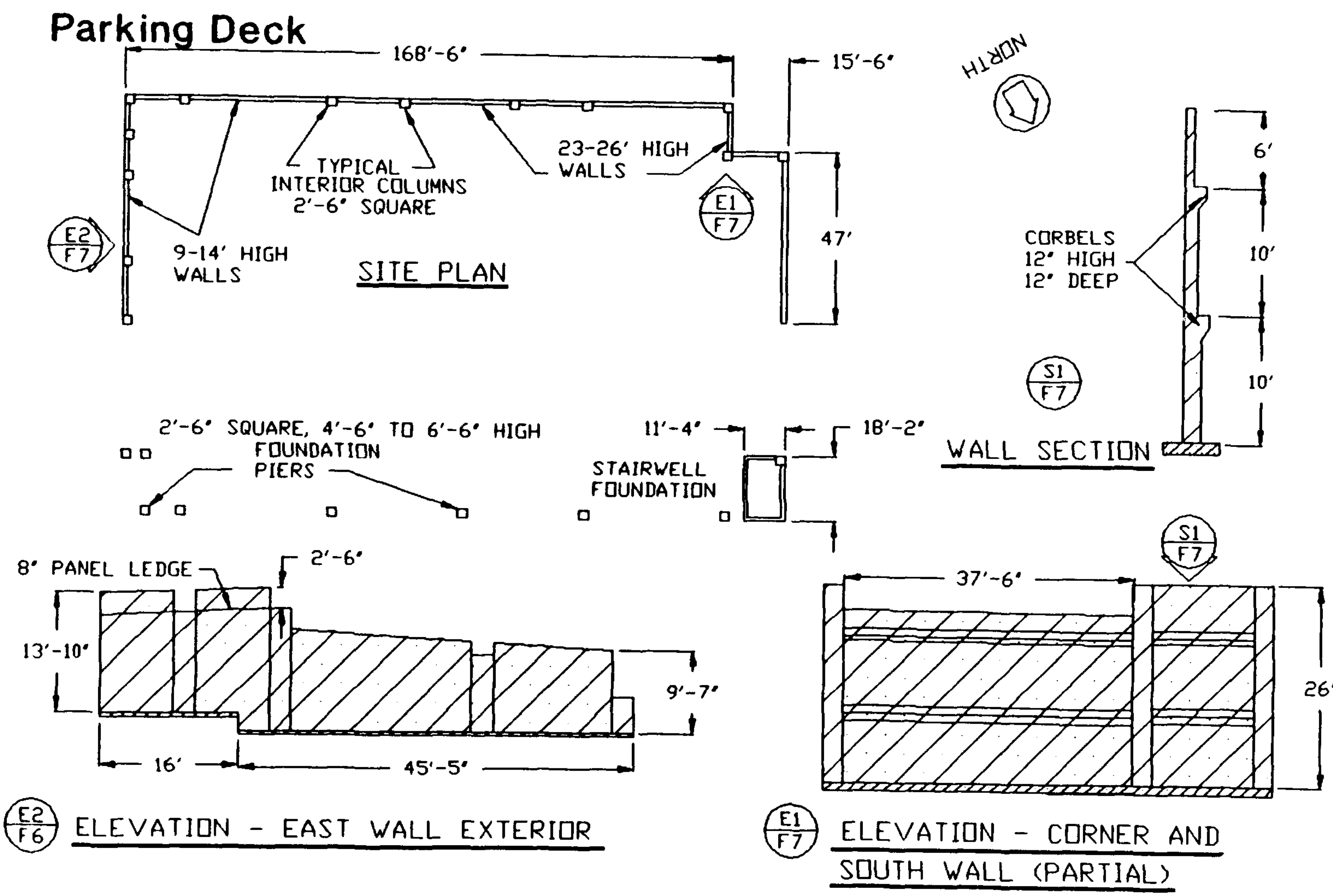

Figure 8. Parking Deck Plan and Views

3.8 Data Collection Difficulties

The major difficulty associated with data collection was the reluctance of contractors to share detailed information. Often the foremen were preoccupied with their duties on site, and could spend little time discussing problems or activities. Foremen and superintendents were often worried that by giving payroll workhours or data on formwork system effects, they would compromise information which competitors might use to bid against them. However, the art museum and parking deck project managers were very helpful and willing to spend as much time as necessary. They provided useful project level information.

Because of the difficulties encountered, data were limited to workhours devoted to formwork activities, quantities, construction drawings, and observable effects. Workhours were separated out for constructing footings, erecting reinforcing steel, pouring concrete, finishing concrete surfaces, and performing detailed form maintenance. However, it was often difficult to distinguish minor form maintenance and supporting work from formwork erection or stripping.

Another problem encountered in data collection was collecting data from several projects concurrently. Output was measured at the end of the workday, but it was impossible to be at two sites simultaneously. Each site was visited daily, but visit times were alternated. Sometimes sites were visited the following morning, before work began.

Collecting and analyzing the necessary data was very time consuming. Careful record keeping was essential. Copies of plans and specific formwork system information are very helpful, especially if they are examined before construction begins. Customized data collection sheets should be used with sketches and photos to record appropriate data. The daily data should be entered into a computerized database within one week to ensure accuracy.

3.9 Data Collection Manual Difficulties

The rules of credit in the Productivity Data Collection Manual should be reviewed. The proposed gang-forming rules of credit in the PDCM should be eliminated. The modular form rules of credit more closely match manufacturer (EFCO 1975) and engineering (Richardson 1989) estimates for gang-form bracing and alignment credit.

The PDCM rules of credit state that cleaning and oiling of forms are incidental, and should not count towards output credit. The PDCM section on daily workhours (Thomas, Smith and Horner 1991, pp. 10-11) stipulates that workhours be counted for organizing storage areas, stacking forms, loading trucks, and similar support activities. The PDCM further requires workhours for scaffolding crews, ironworkers, and formwork oiling and repair crews, be added when supporting formwork erection or dismantling. These

PDCM sections are confusing and should be rewritten. Apparently, credit is not given for cleaning and oiling, but workhours for such are charged to the total.

The PDCM notes that supporting workhours may cause days with little quantity output for significant workhour input. This was observed on all four projects. When a crew stripped, cleaned up, or moved scaffolding, their daily productivity was usually worse than normal. This was clearly expected at the beginning and end of a project, but also occurred in the middle, when a large amount of scaffolding was used or the project site was congested.

Researchers should use separate workhour and quantity accounts for bulkheads, columns, and walls. Hours spent constructing blockouts and boxouts should also be separated. Contractors will often track these separately. However, daily cooperation of each foreman is essential to ensure accurate data collection.

The PDCM does not specify a method of identifying wall heights over 16', footing elevation changes, form materials (not just panel size), and other potentially significant system factors.

Although separate data were obtained for column and wall formwork on the evaluated projects, the two types of data were combined to determine daily and cumulative crew productivity rates, because the overall amount of stand-alone columns was low. Column forms which adjoined wall formwork at the art museum and parking deck were tracked along with the walls. One face was the exterior wall form, and the other sides were part of the interior wall forms.

Daily collection of temperature and relative humidity data as of 1 p.m. seems irrelevant for the studied projects. They had little or no impact on productivity on any observed activity. Perhaps these should be tracked as a significant weather event if they are outside a moderate range of 40-85 degrees and above 80% relative humidity.

3.10 Summary of Data Collection Procedures

The Formwork Productivity Data Collection Manual [PDCM] (Thomas, Smith, and Horner 1991) provides a feasible, standardized method of collecting productivity data on concrete formwork. The PDCM sections on workhours and rules of credit should be revised. Other areas which should be reviewed include work content and environmental/ site conditions. The PDCM already requires a large amount of data, but some additional information may be necessary. Ultimately, the manual serves only as a guide, and will not cover every contingency.

The major difficulty in collecting data on the four studied projects involved access to detailed information from formwork crew foremen on a daily basis. Organizing and analyzing the collected data was challenging and time consuming.

Chapter 4

PROJECT DATA ANALYSIS

This study includes 170 working day observations of formwork crew productivity on four different projects. This chapter analyzes the resulting data to provide insight into the factors which impacted productivity at these worksites.

4.1 Daily and Cumulative Productivity Data

Daily and cumulative productivity rates for each project are displayed in Figures 8-12. Cumulative productivity represents the total workhours per 100 square feet of contact area (SFCA) for the observed activity duration. The plotted data appear to fluctuate greatly among and within projects. However, nearly all these disruptions have one or more identifiable causes. They may result from management factors, rainstorms, or data analysis methods. Productivity for the studied projects was also noticeably impacted by bulkheads, formwork height, boxouts, pipesleeves, corbels, blockouts, and other system factors.

Keyed symbols identify sharp disruptions in each graph. When productivity exceeded 100 workhours per 100 SFCA, plots were truncated to allow better graphical distinction between the remaining days. These productivity spikes resulted from very low or no recorded work output based on the rules of credit. The impact of these spikes will be discussed later.

4.2 Observed Trends among Project Data

The first and second levels of the tertiary filter building were analyzed separately for a number of reasons. Construction of the two levels was separated by a six week period for erecting an intermediate floor slab, elevated filter slabs, weirs, and supporting work. The first level was built below ground level. Wall heights varied between the levels, while different form sizes and types were used.

Productivity for the first level, shown in Figure 8, became worse as the job progressed. Decreased site accessibility and increased complexity of the interior L-shaped wall contributed to this trend. The all-steel forms made penetrations and boxouts difficult to position. Construction of plywood forms to accomodate six large pipesleeves and a watertight door caused the worst delays.

The second level initial productivity spikes, depicted in Figure 9, were caused by form fabrication, poor layout of pipesleeves, and sequencing. The first rainstorm had a greater impact on the schedule than on the project's productivity. Coordination with the ironworkers was a problem. Crew productivity for the last six weeks improved incrementally. Only rain storms, boxouts, and a 42" pipesleeve slowed work during this period. Factors which aided productivity included: better layout, more component repetition, lower baffle walls, less time spent fabricating or reconfiguring forms, and increased gang form usage.

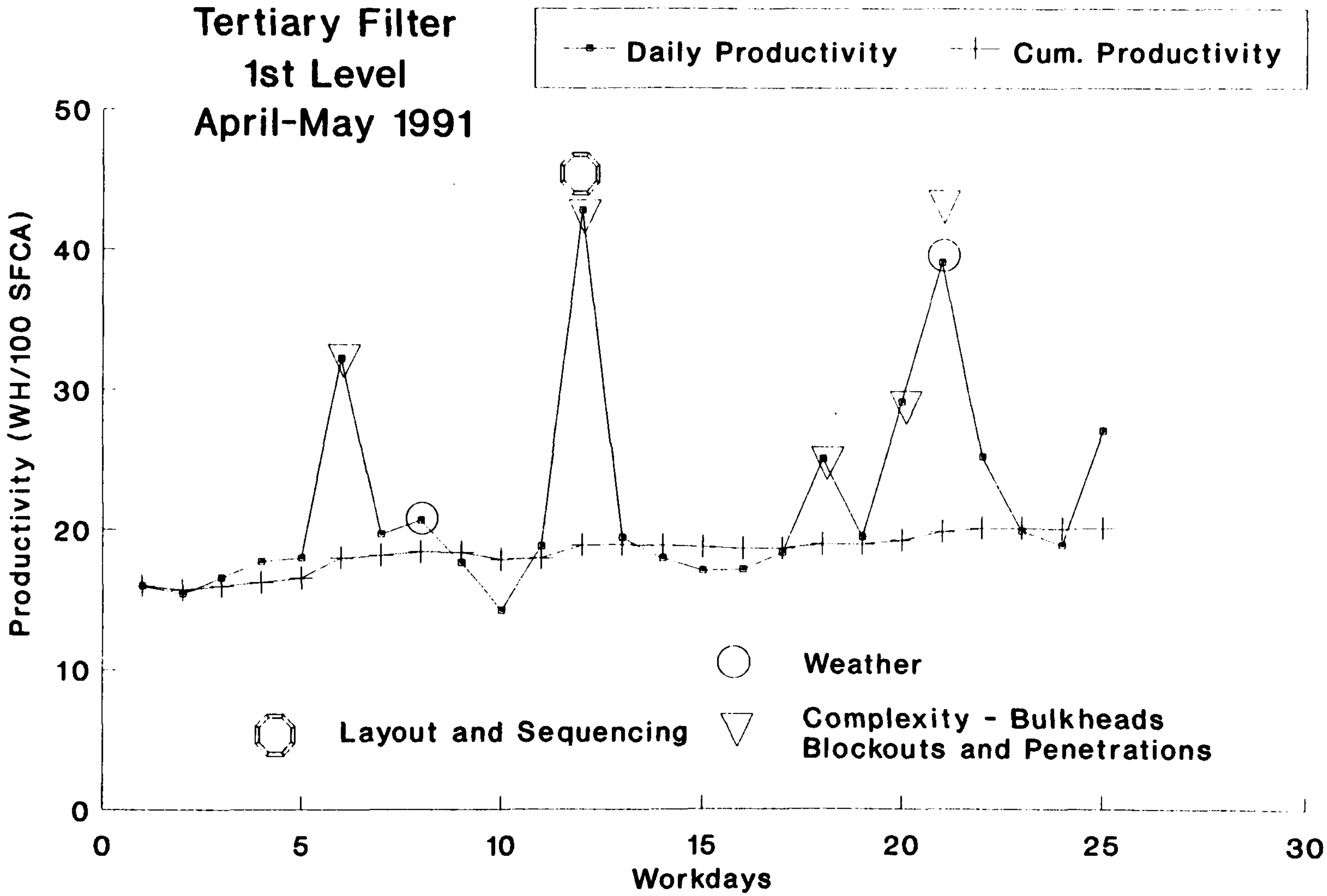

Figure 9. Tertiary Filter, 1st Level Productivity Plots

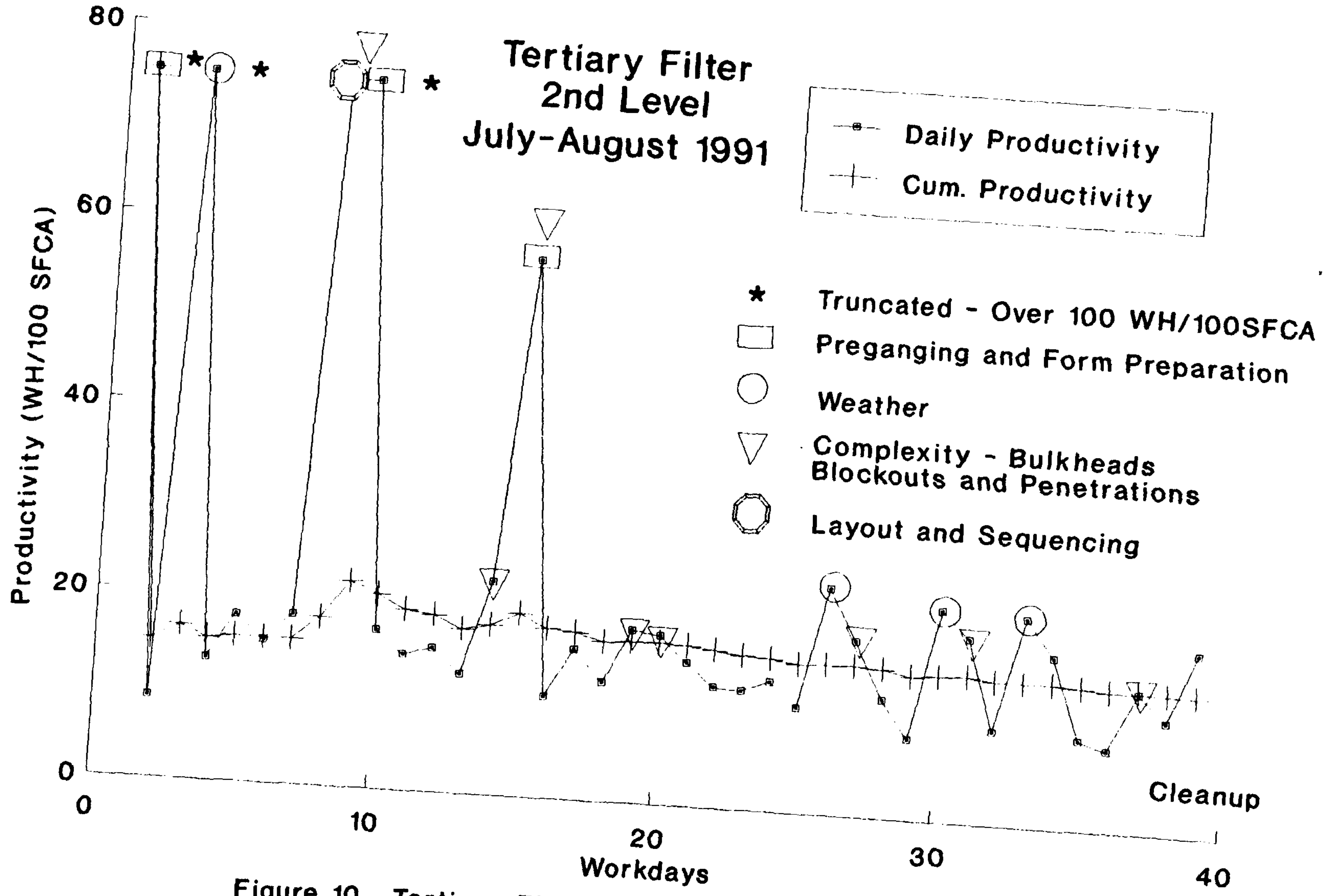

Figure 10. Tertiary Filter, 2nd Level Productivity Plots

The composting facility, displayed in Figure 10, was the easiest project to analyze. After an initial upsurge, productivity generally improved until completion. Form component complexity, bulkhead placement, and rain added to minor startup delays. The repetitive work content of the long, straight walls assisted the overall improvement.

As the upward sloping cumulative productivity curve in Figure 11 indicates, the art museum wing formwork crew's overall productivity became worse as the project progressed. The foundation walls contained numerous blockouts, corners, and integral columns. The utility area located in the northeast portion of the project, included 5 footing elevation changes, a large pier which encased utility lines, and numerous corners. The high south basement wall with its large boxouts also slowed work measurably. Many short wall runs and concrete piers in various locations characterized the later part of the project. This made the job a piecework operation, rather than a full production activity. The small crew was split between footings, rebar, formwork, and support.

The parking deck project productivity, plotted in Figure 12, experienced the widest array of impacts. After initial spikes for form fabrication, the daily rate dipped while the low piers and stairwell foundation were formed. The rate increased as the first and second levels of the L-shaped corner and adjoining south wall were erected. These

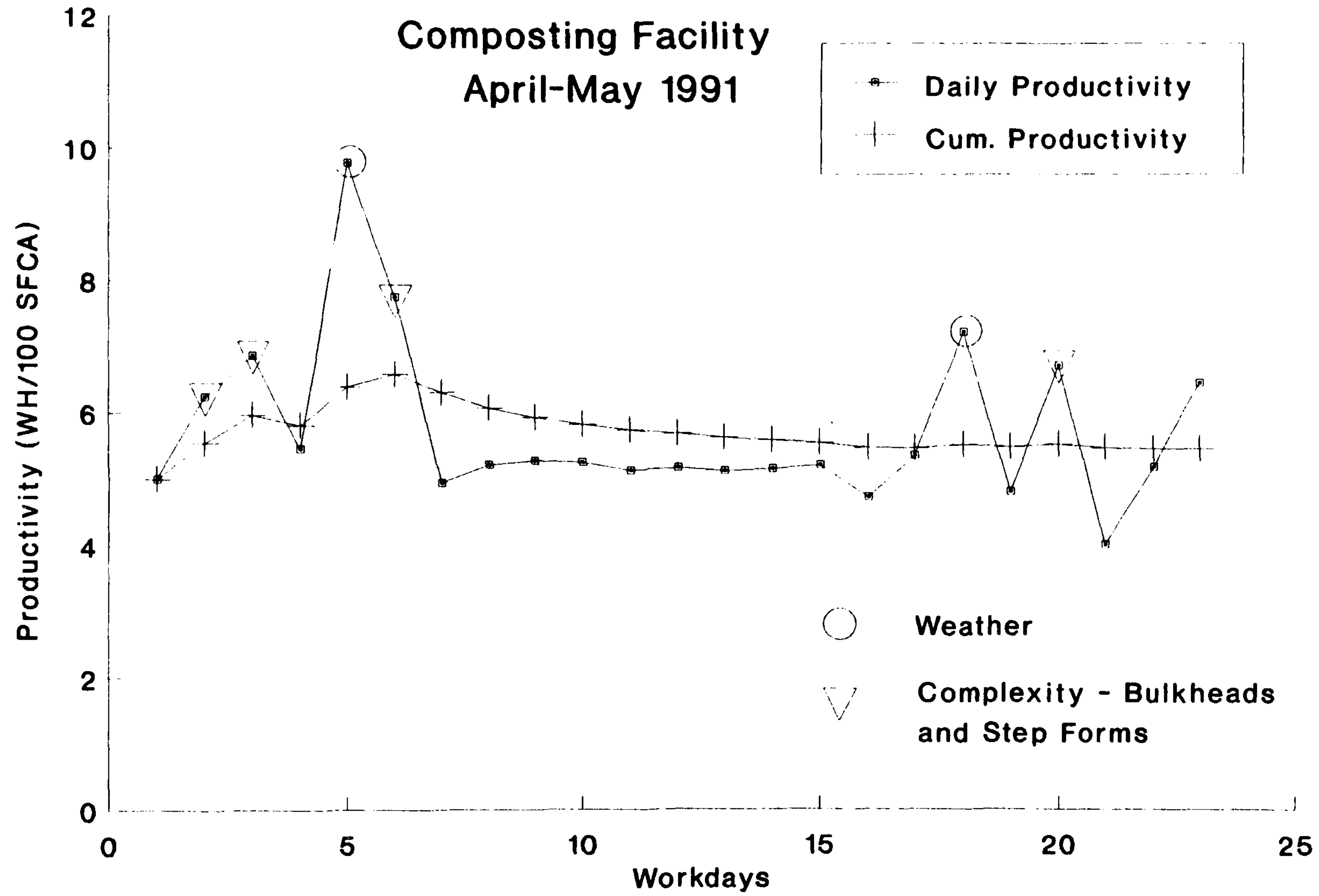

Figure 11. Composting Facility Productivity Plots

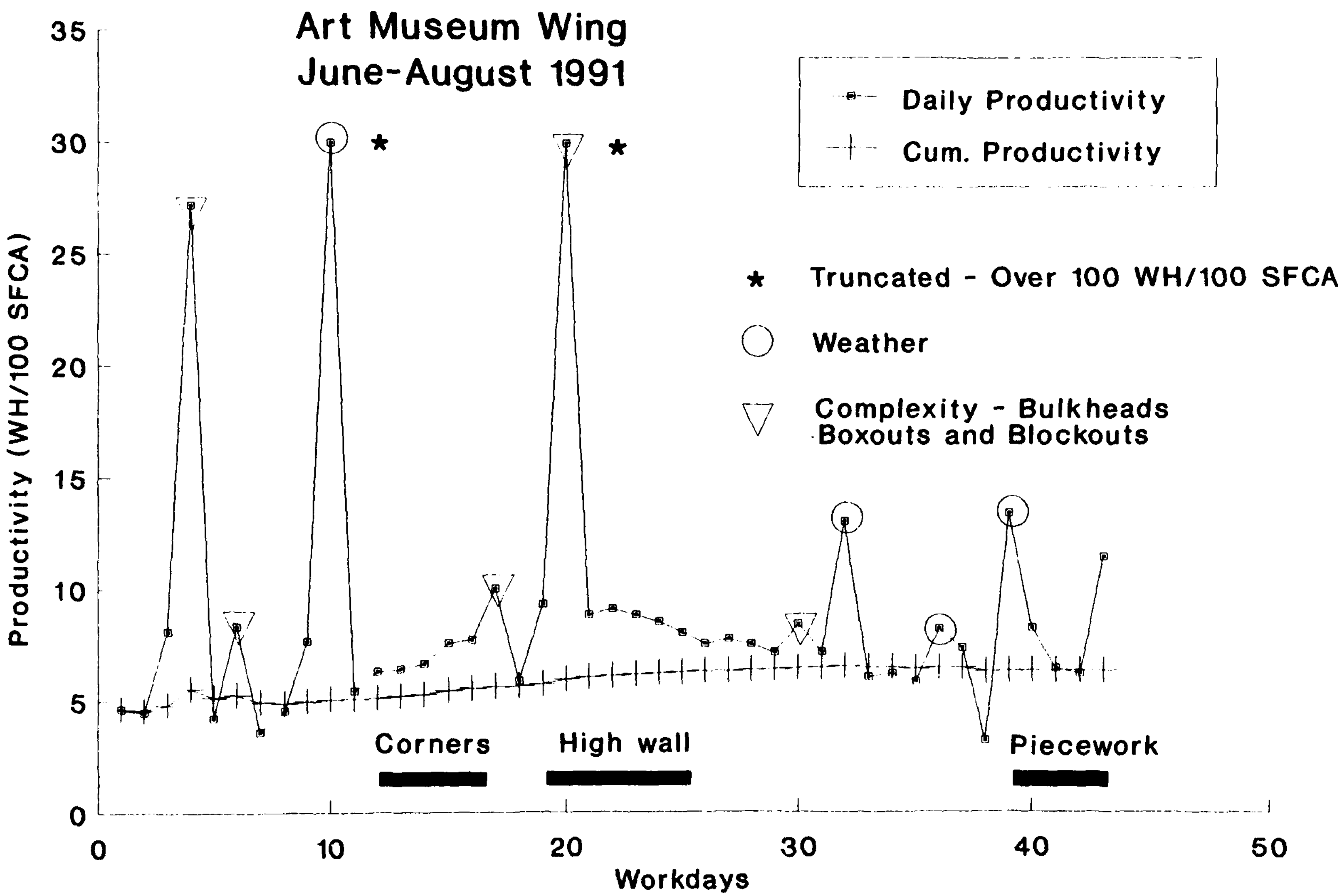

Figure 12. Art Museum Wing Productivity Plots

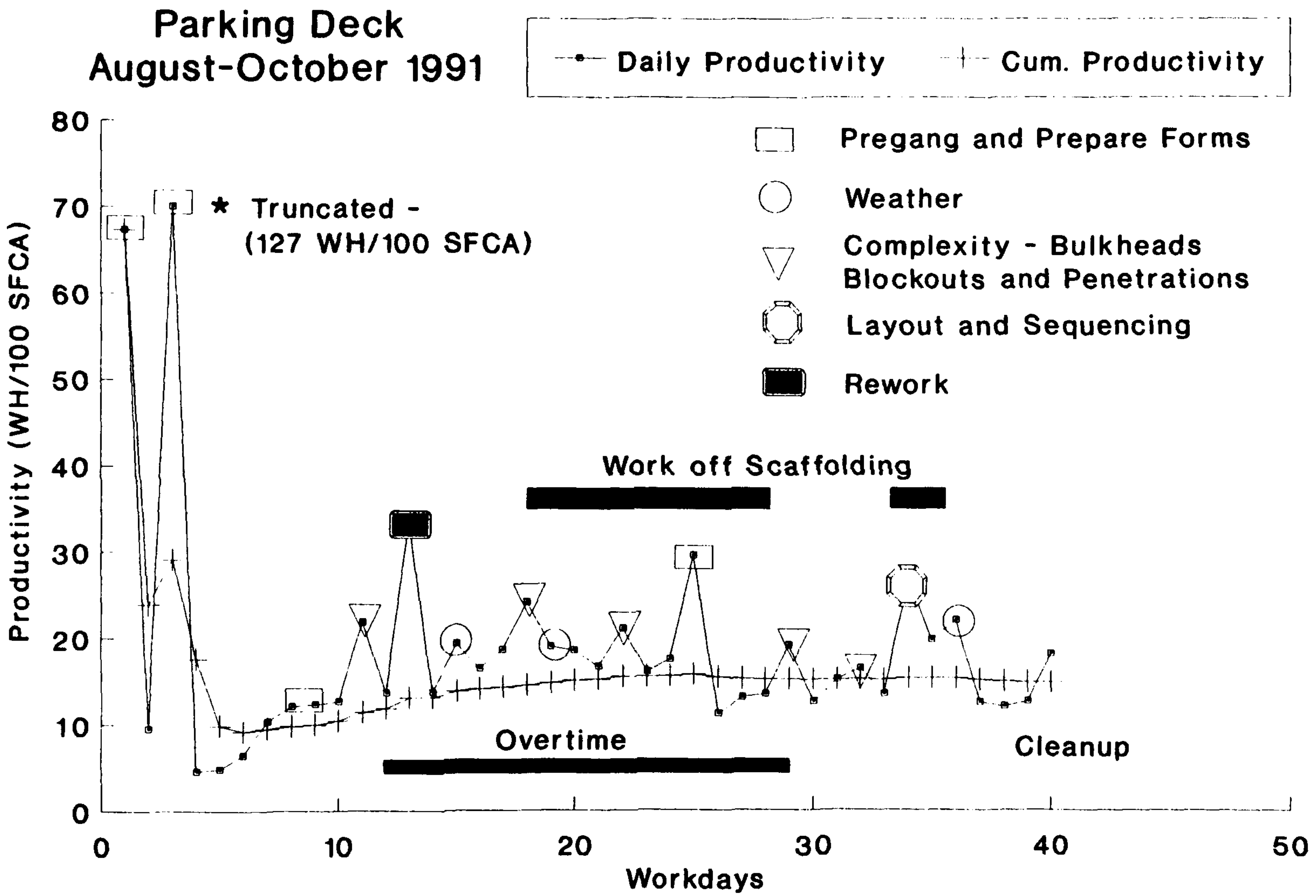

Figure 13. Parking Deck Daily/Cumulative Productivity

walls included integral columns, corbels for beam seats, and were angled. Thickness varied with height, so blockouts were used extensively. Productivity was worst when the crew was working overtime off scaffolding. The rate did improve when the crew finished the lower, less complicated walls at the east end of the project.

In general, the studied projects were of relatively short duration. Craftsmen and laborers often rotated among a variety of activities. This was particularly evident on the parking deck and art museum projects. For example, a crew would pour a footing in the morning, tie rebar in the afternoon, and switch back to erecting forms the next day. This impacted productivity, often in a very subtle way. Partial day rates were usually worse than a full day's work. By contrast, the most stable productivity rates occured at the composting facility where the formwork, rebar, and stripping/cleaning crews were separate.

4.3 Methods and Limitations of Analysis

Some of the important system factors and causes of disruptions have been discussed. Estimating their quantitative impact required the use of statistical tools. This study utilized Lotus 1-2-3 spreadsheets to tabulate and convert various raw data into useful information. The versatile statistical software package, STATGRAPHICS, was used to run analysis of variance (ANOVA) and multiple regression analysis.

The analysis of variance technique was used to determine the effect of conditions like rain, wall height categories, or rework on the dependent variable, productivity. ANOVA calculated a mean productivity rate and 95% confidence interval for each condition, assuming a normal distribution of daily productivity data.

Analysis of variance could not readily determine the relative contribution of an independent metric variable. For example, ANOVA would not calculate the effect of erecting a 5 foot high wall versus a 15 foot wall. This problem was partially mitigated by using categories, such as: up to 8', 8'-16', and higher than 16'.

Another limitation of ANOVA was its sensitivity to productivity spikes and other points outside the normal distribution, called outliers. One daily productivity rate of 500 workhours/100 SFCA would have an enormous effect on both the mean productivity rate and the standard error, when most daily rates were less than 15 wh/100 SFCA. Each data value received equal weight in the ANOVA calculations. Suppose on a disrupted workday 7 workhours were expended, but no measurable output occurred [productivity is infinite, but truncated rate = 500 wh/100 SFCA]. This data spike would be averaged on an equal basis with days where 140 workhours resulted in the output of 933 completed form SFCA [productivity = 15 wh/100 SFCA]. The day with a total of 7 workhours expended would have little effect on cumulative productivity, but a huge impact on the mean rate calculated by ANOVA for an analysis category, such as weather. Due to the potential for skewing data, outliers and spikes were isolated and analyzed independently.

Multiple regression analysis was used to determine quantitative relationships between multiple factors. This was used to validate ANOVA results for varying system factor contributions. This technique was used with caution, as an error in one variable affected the weight given others. With the limited data available, particular attention was paid to statistical indicators like the significance level.

4.4 Specific Analytical Considerations

First, productivity spikes and outliers were separated and analyzed. These were not ignored, but after segregating them, the remaining data could be more clearly analyzed for other factor impacts. Rain halted work in the early morning for one day, for both the art museum and tertiary filter building second level projects. No creditable work was accomplished, but 4-8 workhours were added to the cumulative account before men were sent home. Pipesleeve layout, form fabrication, and boxout construction on several projects caused large productivity spikes where 20-40 workhours were expended, but no wall formwork was erected.

Form fabrication is a special case. Richardson (1989, pg. 3-10-2) allocates 16 workhours/200 SFCA for gang form fabrication. When prorated over 4 uses, this accounts for 59% of the estimated erection and bracing time. The current rules of credit do not recognize the contribution of prefabrication. However, if 2/3 of the wall erection credit and 1/3 of the bracing credit are given the day the form is fabricated, the average resulting credit for both wall sides is 57% of the allocated erection and bracing time. This estimate was used to calculate production rates for those days when productivity spikes occured due to preganging or fabrication.

After the major data spikes were isolated, the impact of less severe disruptions such as rain, rework, or sequencing could be evaluated. These were compared to the mean productivity rate for the remaining non-impacted data, using ANOVA. From this comparison, disruption productivity influence factors (PIFs) were calculated.

After removing disrupted productivity data, the remaining days were examined for the impact of general and system factors which spanned several days or weeks. These included the effects of repetition, high walls, gangforming, and overtime. Though some factors overlapped, careful analysis yielded fair estimates of PIFs.

The revised data set was separated into non-impacted, impacted by system factors, piecework, and support work categories. As the projects ended, crews typically finished small wall sections, columns or other miscellaneous work. Productivity for these piecework sections was usually worse than normal production days. Supporting work involved cleanup, erecting scaffolding, moving forms, and other accountable work which resulted in little output. Piecework and supporting work may be partly responsible for what some term the "end effect" (Bennett 1990, pp. 42-44).

After removing disrupted, piecework, and supporting work days, the data sets were evaluated for specific system factor effects. The ANOVA technique was used to compare impacted rates identified by the predominant system factor such as bulkheads. Then multiple regression was employed to estimate coefficients for overlapping factor effects and to contrast the PIFs calculated by ANOVA.

4.5 General Factor Impacts

The impact of general factors on productivity is shown in Table 5. The mean disrupted productivity rate for each project is given, disregarding spikes. The associated productivity influence factor (PIF) was calculated using the mean productivity rate for days not impacted by that factor.

For the combined projects, rain precluded work on 2 days, ended work after only two hours on 4 other days, and moderately disrupted productivity on an additional 10 days. However, rain had little or no effect on 12 workdays. In fact, the tertiary filter building crew displayed better

Table 5. General Impact Productivity Influence Factors

Projects using Gangforms and Handset Modular Forms:

Factor	Tertiary Filter Bldg. 1st Level	Tertiary Filter Bldg. 2nd Level	Parking Deck	Average
Weather	1.49	(Spike >33) 1.44	1.29	1.41
Rework	----	----	2.24	2.24
Sequencing & Layout	2.14	(Spike >33)	1.77	1.96
Overtime	----	----	1.07	1.07
Repetition	----	0.87	0.87	0.87
Piecework	----	1.32	----	1.32
Cleanup/Support	1.29	1.52	1.43	1.41

Projects using only Handset Modular Forms:

Factor	Composting Facility	Art Museum	
Weather	1.54	(Spike >33) 1.52	1.53
Repetition	0.83	----	0.83
Piecework	----	1.85	1.85
Cleanup/Support	1.37	2.03	1.63

(1) Table 5 and Table 6 (pg. 62) display Productivity Influence Factors [PIFs] calculated using data from the observed projects.

(2) The PIF equals the impacted productivity rate divided by the unimpacted or base rate.

than average productivity on two days with intermittent heavy rain. Morning rain usually had a greater impact on productivity than afternoon rain. The four project average PIF for rain was 1.47.

Absenteeism was low on all projects, but when it occurred, poor weather and overtime were contributing factors. No overtime hours were incurred by the art museum or composting facility contractors. They often worked 9 or 10 hours four days a week, but took time off on Friday. The tertiary filter building crew worked 44 hours a week, with one hour of overtime each day, Monday through Thursday. The effect of overtime on these projects was not discernible from the collected data.

The parking deck project experienced the worst impact from overtime. They began the project working four 10 hour days per week. When the project became 2 1/2 weeks behind schedule, the crew worked 18 consecutive ten hour days, including one 74 hour week. Productivity during this period was worse, though the component attributed to overtime was partially obscurred by wall height and other system factors. The estimated PIF for overtime on the parking deck was 1.07.

The tertiary filter building contractor experienced sequencing and coordination problems with a subcontractor. On two occasions, the ironworkers did not show up because they were diverted to another project. The formwork crew encountered initial delays when penetrations and boxouts required rebar to be cut or bent. The foreman was also uncertain of the layout for pipesleeves and a watertight door. This management information problem contributed to two major disruptions and two other delays. In addition to a large productivity spike, the resulting sequencing and layout PIF was 2.14 for the tertiary filter building.

The layout and sequencing problem shown for the parking deck resulted when the crew had to return to a previous area, set up scaffolding and form a small 6 foot long section of the high 26' wall. The placement of construction joints and a compressed schedule contributed to the impact of these disruptions [PIF = 1.77]. The combined average layout and sequencing PIF was 1.96.

Rework was a greater factor than the productivity plots indicate. The largest single impact of rework was on day 13 [PIF = 2.24] at the parking deck. As the crew was ready to pour, the superintendent noticed that one inclined corbel form was 2 inches higher than permissible. The crew removed about 35 panels, modified the corbel form, and replaced the panels. Several other times on the parking deck project, panels were removed to retrieve objects, reset spreaders, or make other adjustments. This also occured to a lesser extent on the other projects. The plots do not reflect such incidents, which were frequent, but of minor consequence.

After reviewing the performance of crews erecting similiar component sections, three projects displayed productivity improvements through repetition of 0.83 to 0.87. This improvement is partially reflected in the gang forming PIF calculated in the next section.

The art museum displayed the largest impact from piecework with a PIF of 1.85. The productivity influence factors for supporting work and cleanup ranged from 1.29 to 1.85 when considering all projects.

4.6 Analysis of System Factor Impacts

The overall system productivity influence factor for each project is a measure of the system complexity. Table 6 presents the PIF values estimated using primarily ANOVA, with multiple regression corroboration. These values might be expected to vary substantially between projects. However, the overall values for the two gang formed projects are fairly similar [1.34-1.53]. These projects were fairly complex, so this is not too surprising. The relative complexity of the art museum [PIF = 1.90] to the composting factility [PIF = 1.27] is clear.

Wall height, gang-forming, and form type are fairly simple to isolate on a daily basis. Days when 6 foot high walls were constructed are simple to compare with days when 17 foot high walls were erected.

Other system factors such as corners, bulkheads, boxouts, and corbels have a more quantity sensitive impact. The number, size, shape, and other characteristics of these

Table 6. System Impact Productivity Influence Factors

Factor	Tertiary Filter Bldg. 1st Level	Tertiary Filter Bldg. 2nd Level	Parking Deck	Average
Overall Effect	1.34	1.53	1.37	1.41
Gang Forming	---	0.78	0.91	0.85
Wall Height [Compared to the base rate for walls < 8' high]				
8'-16'	----	unable to	1.95	1.95
>16'	----	determine	2.28	2.28
Multiple Factors	1.55	1.62	1.59	1.59
Corners	1.02	1.05	1.36	1.14
Bulkheads	1.10	1.18	1.54	1.27
Boxouts	1.80	1.24	----	1.52
Penetrations				
Large (42")	1.99	1.57	----	1.78
Medium	1.26	1.36	----	1.31
Blockouts	----	----	1.31	1.31
Corbels	----	----	1.33	1.33
Pilasters	----	1.17	----	1.17

Factor	Composting Facility	Art Museum	Average
Overall Effect	1.27	1.90	1.55
Wall Height [Compared to the base rate for walls < 8' high]			
8'-16'	----	1.04	1.04
> 16'	----	1.75	1.75
Form Size [smaller]	1.09	----	1.09
Multiple Factors	----	2.75	2.75
Corners	----	1.58	1.58
Elevation Changes	----	1.65	1.65
Bulkheads	1.04	1.71	1.38
Boxouts	----	1.91	1.91
Column and Beam Seats	----	1.68	1.68

formwork components affect their associated PIF. For example, a day when 32 linear feet of corner forms were erected is less influenced by corners than a day when 64 linear feet of corner forms were built. Multiple regression is more useful than ANOVA in analyzing these types of PIFs. Multiple regression estimates the relative influence of these factors based on the quantity erected as a percentage of the total work involved.

4.6.1 Gang Forming

The tertiary filter building and parking deck project used some gang forming, but exhibited worse average productivity than the exclusively handset modular form projects. However, both projects involved high walls with numerous blockouts and complicated shapes. Gang forms were used because heavy bracing was required and to reduce work from scaffolding. Sections could be assembled or ganged easily on the ground and swung into place by crane. After initially poor productivity due to form fabrication, both projects displayed improvements because of gang forming and repetition. The tertiary filter building, 2nd level PIF of 0.78 was more impressive than the parking deck PIF of 0.91. The parking deck contractor encountered problems using gang forms for the sloping walls and varied wall heights, with changing corbel form inserts, and around adjoining columns.

4.6.2 Wall Height

Walls were separated into three height categories for analysis. The base rate was the mean value for walls under 8′ high. The other categories were 8′ to 16′ high, and over 16′ high. It was impossible to determine wall height impacts on the tertiary filter building 2nd level, though the low baffle walls seemed to contribute to improvement in productivity. Both the parking deck [PIFs = 1.95 and 2.28] and art museum [1.04 and 1.75] exhibited higher PIFs than the estimating manuals predict [1.26 and 1.43]. However, the high walls for both projects contained numerous large boxouts, blockouts, and other complicating features.

4.6.3 Form Size and Type

The predominant form size and type used on these projects was a 2′ by 8′ steel framed plywood faced panel. This size, along with the 2′ by 6′ panel appeared to be the most efficient. The 2′ wide steel framed plywood panels were also very effective when used for gang-forming.

Smaller forms were generally required for corners, thus a higher PIF resulted when smaller panels were used. The smaller step forms described for the composting facility exhibited a PIF of 1.09.

The all-steel panels used for the tertiary filter building 1st level slowed productivity because plywood filler forms were required to situate the large 42" pipesleeve and watertight door. The parking deck crew also experienced some delays in positioning rebar spacers, spreaders, and boxouts on the all-steel panels. The plywood faced forms used on the other projects allowed easier attachment of hardware.

4.6.4 Corners and Elevation Changes

Corner impact factors were low for the tertiary filter [PIF = 1.02-1.05]. These projects had relatively simple long, straight corners at wall intersections. The art museum [PIF = 1.58] and parking deck corner [PIF = 1.36] values were much higher because of the integral piers and columns formed in the walls. The art museum productivity also suffered noticably [PIF = 1.65] when footing elevation changes were encountered.

4.6.5 Bulkhead Placement

Bulkhead productivity influence factors range from 1.04 for the composting facility to 1.71 for the art museum. The composting facility had the most bulkheads, but all were identical. The bulkheads for the parking deck were the most complicated because of the varying wall thicknesses between levels. The art museum bulkheads were not unusually difficult, which would tend to discount the high PIF as a statistical anomaly.

4.6.6 Boxouts and Penetrations

The highest boxout PIF [1.91] occurred at the art museum. This resulted from the large boxouts constructed in the high south basement wall. The watertight door in the tertiary filter building also caused a large PIF [1.80].

Pipesleeve placement for the tertiary filter building caused large penetration PIFs of 1.26 to 1.99. The 42" pipesleeves had much more impact than 18-30" pipesleeves.

4.6.7 Blockouts, Corbels and Pilasters

Blockouts and corbels had nearly equivalent impacts on the parking deck project [respective PIFs of 1.31 and 1.33]. Their purpose, design, and construction are very similar. The pilaster on the south wall of the tertiary filter building 2nd level only caused a PIF of 1.17. Pilaster forms were reused, which reduced the impact.

4.6.8 Multiple Factor Effects

Often, several of the above factors would interact. The resulting multiple impact PIFs were very similar for the two gang formed projects [1.55-1.62]. However, the art museum showed a drastic PIF of 2.75. This project was susceptible to this drastic PIF due to the piecework nature of the job, small crewsize, and the significant system factors involved the affected workdays.

4.7 Summary of Data Analysis

The data analysis technique involved the use of visual examination of productivity plots, analysis of variance for impacted productivity rates, and multiple regression. Productivity influence factors (PIFs) were calculated by dividing impacted productivity rates by nonimpacted rates for specific disruption categories, general productivity factors, and system factors.

The resulting PIFs indicate the average quantitative impact which weather, overtime, rework, and system factors had on the observed projects. The PIF values were similar to values presented in Chapter 2. These values may be useful in developing forecasting model factors.

PIF values for many system factors depend upon the relative quantities erected on a specific day and component complexity. For example, the bulkhead PIF will most likely be different from one project to another. The PIFs given for these factors in Table 6 were the overall or net PIFs on days when a distinct impact was observed due to these factors. Appendix C contains the statistical analysis summary information. This area requires greater research to improve the usefulness of system factor PIF values.

Chapter 5

COMPARATIVE FACTOR ANALYSIS

The productivity influence factors [PIFs] presented in Chapter 4 are generally similar to those provided by the literature. This chapter examines the agreement and differences between undisrupted productivity rates and PIFs given by project data, industry sources, and past research.

5.1 Comparison of Base Rates between Projects

The base or undisrupted rates calculated for the projects by ANOVA or multiple regression vary widely. The first level of the tertiary filter building had an average undisrupted rate [15.95 WH/100 SFCA] 29% higher than the undisrupted productivity for the 2nd level [12.39 WH/100 SFCA]. In turn, the tertiary filter building 2nd level undisrupted rate was 27% higher than the parking deck undisrupted rate [9.74]. Clearly, the projects which used gang forming showed a wide range of "undisrupted" rates.

The causes for such variance extended well beyond disruptions or simple system factors. These chronic root causes included management practices, material management, site organization, crew experience, system inefficiencies, and other factors which impacted productivity throughout most or all of the activity duration.

Foremen were switched on the tertiary filter building just prior to beginning the first level, and the crew was inexperienced. The foreman split his time between several other activities during construction of the two levels. This reduced effective information transfer between management and the workforce. Considering the lack of information availability and a high level of complex, interdependent work sequences, this seemed to be a classic case of poor constructability (Chapter 2, page 13). The large steel forms used on the first level slowed production. Limited access to the work and the absence of a firm completion date added to the higher overall rates on both levels. The crew seemed to reach a plateau with an artificially slow work tempo.

The parking deck project initially fell behind an already tight schedule, and the crew struggled to make up the lost time. Information transfer after the first few weeks, seemed better on this project than the tertiary filter building. The superintendent managed only one activity, and worked directly with the crew. The south wall contained long, straight sections and repetition partially mitigated complex work items such as corbels and blockouts. The all-steel forms used throughout the project may also have contributed to worse "undisrupted" productivity.

The entirely handset modular form projects showed better overall productivity, and better agreement between undisrupted rates. The mean art museum undisrupted rate

[4.33 wh/100 SFCA] was about 5% lower than the average composting facility undisrupted rate [4.57 wh/100 SFCA]. This small difference is not significant.

The composting facility was the simplest project to manage in terms of work content, and information flow was good. The crews focused on one type of work, rather than moving between activities. The work tempo was fairly constant, but not optimal. Daily goals were defined, and crews showed little intention to exceed set levels.

The art museum foreman worked directly with the small crew, so information exchange was best on this project. The foreman set a steady pace, when bulkheads, boxouts, and other system factors did not affect crew performance. This project showed the widest fluctuations compared to the undisrupted productivity rate. The low output quantities and small crew size contributed to this fact.

The better overall productivity on the two handset projects resulted from better information flow, better site access, lower average wall height, ease of modular form use, and fewer complex, interdependent work sequences.

5.2 Comparison of Base Rates to Industry Research

Manufacturer supplied information was understandably optimistic. However, the rates were based on actual project data from company records (EFCO Rate Sheets 1975) and from outside researchers (Adrian 1975b). The base rates for most modular forming systems ranged from 2 to 4 workhours per 100 SFCA. Gang forming values were 1.5 to 3 workhours per 100 SFCA. Adrian (1975b, pg. 15) provided base rate data for column forming of 4.56 to 5.65 WH/100 SFCA.

Estimating manuals were more conservative. Modular form base rates ranged from 7-9 WH/100 SFCA (Richardson 1989 and Means 1986). The manuals estimated gang-forming rates from 6.5 to 8.5 WH/100 SFCA.

Calculated project base rates for this study varied from these rates substantially. In addition to the management, constructability, and site factors described previously, the inclusion of column data into the primarily wall forming projects added to the base rate estimate. Information flow and the work tempo mantained by management and the crew also impacted the base rate variance.

5.3 Comparison to Other Research Base Rate Results

The values given by industry and estimating manuals were derived from data collection systems which differed substantially from the one used in this thesis. Other research using data collection and analysis procedures similar to this study yielded quite different results. Bennett (1990, pg. 48) measured a mean "undisrupted" productivity rate of 46 workhours per 100 SFCA. This rate was calculated without removing system factor impacts. The estimated actual undisrupted rate was probably less than 30.

Yiakoumis (1986) found an undisrupted rate of 16 workhours per 100 SFCA which was closer to those observed in this study. These values, plus those obtained from other sources, provide limiting bounds for base rates.

5.4 Comparison of PIFs to Other Sources

Many project productivity influence factors matched the values provided by literature well. For example, rework, gang forming, and repetition PIFs were within 10% of the literature provided values.

Weather event PIFs were lower than those given by Bennett and others, if the two rain-out days were excluded. This was expected, as the impact of rainstorms would vary based on duration, intensity, time of day, and other variables. The data were also collected during a dry year.

The piecework and cleanup/support PIFs could not be directly compared to a value from the literature. However, Adrian (1975b, pg. 43) and the EFCO Rate Sheets (1975) calculated a value for stripping [cleanup/support] which compared to the credit applied in this study works out to a PIF of 1.4. This was not far off the calculated average PIF of 1.52 for cleanup/support. Adjusting the rules of credit to allow 15% credit for stripping and moving formwork would reduce, though probably not eliminate this effect.

Wall height varied significantly from the estimated literature rates for the parking deck, but slightly less for the art museum. This was attributed to other system and general factors which obscured the influence of height.

Other system factor influences are dependent on quantity, dimensions, location, component complexity, and other variables. These include bulkheads, boxouts, penetrations, corbels, pilasters, and other blockouts. The PIFs provided by the literature span a broad range, but they are only rough estimates for an average impacted area. The influence may be very small or large. For example, if a boxout occupied 5 square feet of wall area, but 500 SFCA were erected on that day, the impacted area would only be 1% of the total output quantity. If a large 10' by 14' boxout [140 SF] were built when 200 SFCA of wall were erected, the boxout impacted area would be 70% of the daily output.

To illustrate the effect, several comparative analyses were done for this thesis. For example, the tertiary filter building 2nd level had an average boxout impacted area of about 15% on days when boxouts were constructed. The literature provided an average PIF value of 2.0 for boxouts. The corresponding estimated PIF for boxout impacted days was 1.3 [(standard output x 1) + (0.15 x 2)]. The boxout PIF from ANOVA was 1.24, and the value calculated by multiple regression was 1.18. The lower values from project data analysis resulted from the simpler nature of boxouts for the 2nd level, compared to the tertiary building 1st level and the art museum. Obviously the values from the literature and project data analysis were much closer when converted to represent their relative contribution to total output.

5.5 Comparative Analysis Summary

The base rates and PIFs examined by this chapter are compared in Table 7. Manufacturer provided base rates of 1.5 to 3.5 workhours per 100 SFCA, though based on actual projects, appeared optimistic. Estimating manuals were more conservative at 6.5 - 8.5 workhours per 100 SFCA. Local project "undisrupted" daily rates ranged from 4.33 to 15.95 workhours per 100 SFCA. Other studies using similar data collection systems indicated "undisrupted" rates were 16 to 46 workhours per 100 SFCA.

Many project PIFs matched well with values provided by the literature search. This was particularly true for general factors like overtime and rework. Project rework, gang forming, and repetition PIF values were all within 10% of the values provided by literature. The influence of weather was highly variable, but rain displayed a smaller impact in this study than in previous work.

System factor PIFs for bulkheads, corbels, corners, and other area dependent factors vary widely. The PIFs obtained from literature applied only to the impacted area, not the entire output quantity. They had to be adjusted before they were compared to overall project calculated PIFs. Once adjusted, most compared well to project calculated rates.

Table 7. Comparative Base Rate and PIF Analysis

Item	Industry Sources	Other Sources	Project Average	Overall Average
Base Rate (WH/100 SFCA)	2-8 [Range]	16-46 [Range]	4-16 [Range]	2-46 [Range]
PIFs	Net or Overall for Daily Productivity			
General:				
Weather	----	2.0	1.52	1.76
Rework	----	2.44	2.24	2.34
Overtime	----	1.06+	1.07	1.07+
Layout	----	2-4	1.96	2
Piecework	----	1.4 **	1.6	1.5
Cleanup	----	1.6 **	1.53	1.56
System - Area independent				
Overall	----	----	1.46	1.46
Gang Forming	0.85	0.79	0.85	0.83
Wall Height				
8'-16'	1.21	----	1.50	1.36
Over 16'	1.37	----	2.02	1.70
Form Size (< 2' x 8')	----	----	1.09	1.09
Form Type (Steel)	----	----	1.29	1.29
System - Area or length dependent [Converted to net]				
Multiple	----	----	1.88	1.88
Bulkhead	1.3	----	1.31	1.31
Corners	1.5	5.0	1.25	1.37
Elev. Changes	----	----	1.65	1.65
Boxouts	1.5	----	1.65	1.58
Penetrations				
Large	1.5	----	1.78	1.64
Medium	1.5	----	1.31	1.40
Blockouts				
Ledges	1.5	----	1.31	1.40
Pilasters	1.5	----	1.17	1.33
Corbels	1.5	----	1.33	1.41
Benches	1.5	----	1.68	1.59

** Piecework and cleanup/supporting work PIFs were calculated from Bennett's data (1990) using "end effect" and output flagged data.

Chapter 6

SUMMARY, FINDINGS, AND RECOMMENDATIONS

This thesis identified factors which influence concrete formwork productivity and analyzed their quantitative impact. Current data collection procedures were also reviewed. This chapter summarizes study findings and presents recommendations for further work in these areas.

6.1 Summary

To effectively exchange information on formwork crew productivity, researchers must employ consistent terminology and use similar data collection methods. This thesis used and evaluated methods presented in the Procedures Manual for Collecting Productivity and Related Data: Concrete Formwork (Thomas, Smith, and Horner 1991), referred to by this study as the Formwork Productivity Data Collection Manual, or PDCM. Productivity was defined as the labor workhours required to construct 100 square feet of contact area (SFCA) of finished formwork.

Research from various universities, literature provided by formwork manufacturers, and estimating manuals identified many factors which impact productivity, and provided a basis for evaluating their quantitative impacts. For this thesis, a productivity influence factor [PIF] was calculated by dividing the impacted productivity rate by the non-impacted productivity rate to determine the influence of rain, rework, and other effects.

Gang forming, effective coordination, proper material management, and repetitive components may improve productivity. Disruptions, which dramatically degrade productivity, may result from severe weather, accidents, labor disputes, rework, or other causes. Factors like overtime, improper sequencing, change orders, and constructability may degrade long term productivity.

Elements which defined formwork constructability, based on formwork requirements and the geometric shape of structural members, were called system factors. These included form type, shape, height, placement method, bulkheads, boxouts, corners, connection hardware, pilasters, corbels, haunches, and other form system characteristics.

Chapter 3 explained productivity data collection at four local project sites using PDCM procedures. The projects included a wastewater tertiary filter building, a composting facility, an art museum extension, and a 3-level parking deck. The data collection process revealed a need to collect more information on system factors like wall height, footing elevation changes, and complicating features like corbels. The rules of credit were reversed, and the section on workhours was confusing. Obtaining detailed information from formwork crew foremen on a daily basis was the biggest challenge involved with data collection.

Data from the four projects were analyzed to determine productivity rates and corresponding productivity influence factors in Chapter 4. Impacted and non-impacted mean productivity rates were determined using computerized statistical tools such as analysis of variance and multiple regression. PIFs were calculated for weather, overtime, rework, wall height, and various system conditions.

In Chapter 5, PIFs for the four projects were compared to those obtained from the literature search. Values were similar for most general factors. The influence of weather was less than predicted by some literature. System related PIFs calculated for wall height, corners, and boxouts differed widely between projects. However, these PIFs were within the predicted range from estimating manuals. For example, the average overall bulkhead PIF for the projects was 1.31 while the average bulkhead PIF derived from the estimating manuals was 1.30. Factors due to piecework, cleanup/support, and elevation changes were not well documented.

Ideal productivity base rates, free of disruptions and other influencing factors, should be similar. Isolating such base rates was difficult. The "undisrupted" base rates cited by other researchers ranged from 1.5 to 46 workhours per 100 SFCA. The "undisrupted" rates for this study were 4.33 - 15.95 workhours per 100 SFCA. This variance resulted from various site and management related factors.

6.2 Findings

Previous literature identified a number of critical factors and estimated their quantitative impact. To present consistent values, this study introduced a standard productivity influence factor [PIF], which measured the impacted rate divided by the unimpacted rate. A PIF higher than 1 indicated that productivity was worse in the presence of a particular condition such as rain [1.4-2] or rework [2.24]. A PIF lower than 1, indicated that productivity would improve if repetitive components [0.80-0.87] or effective coordination [0.80] were employed.

Productivity influence factors provided a dimensionless quantitative basis of comparison for the impact of various general and system causes. The relative complexity and sensitivity to system factor impacts for projects was reflected by the overall system factor PIF. For example, productivity for the art museum was complex and sensitive to system factors [PIF =1.90], while the composting facility was much simpler and less sensitive [PIF = 1.20].

The PIF may also be multiplied by an unimpacted base rate to estimate the impacted rate. This suggests their potential for use in productivity forecasting factor models.

Weather events had little or no impact on 12 observed days, but work was precluded on two rain days. The impact on other days was significant [PIF = 1.47], but not as large as previous work indicated [PIF = 2.0]. This was the greatest variance in comparing general factors, but was not unusual considering the variable nature of weather events.

Wall height PIFs observed on projects were highly variable, but other system factors interfered with the analysis. Considering these factors, the impact of wall height was not far off what other literature indicated.

Some system factors such as gang forming had a consistent influence on productivity [0.80-0.95]. However, the impact of others such as bulkheads, boxouts, and corners, varied widely based on the quantity, size, shape, and complexity involved. PIFs available from estimating manuals were based on the type and quantity involved. This effect was difficult to isolate from project data using ANOVA. Regression analysis was a better tool to use, but was limited due to the small amount of available data.

If the system factor impacted area was compared to total daily output, the project determined PIF was close to the literature PIF. For example, on one day, bulkhead SFCA was 5% of the total daily output. The literature provided a PIF of 3.5 for that type of bulkhead. Therefore, the effective PIF for bulkheads was 1.18 [(daily output x 1) + (0.05 x 3.5) = 1.18]. This example matched the bulkhead PIF calculated for the tertiary filter building 2nd level.

System factors like complicated boxouts and large pipesleeves not only slowed productivity on the observed projects, they caused layout, sequencing, rework, and other disruptions as well. These factors have a huge impact on productivity which should be isolated to avoid misallocating the influence to another source during analysis.

The influence of predominantly piecework and cleanup/ supporting work days resulted in average project PIFs of about 1.6 and 1.5 respectively. This had been previously noted as an "end effect," but was observed on several projects during the middle of an activity. These days should also be isolated from other "non-disrupted days."

The formwork productivity data collection manual [PDCM] is basically sound, but several sections should be modified. The present rules of credit for gang forming should be eliminated. The rules of credit for modular forming are more flexible, and account for bracing and alignment better. Rules of credit for pre-erection gang form fabrication would also allow more realistic productivity analysis. These were estimated in this study at 2/3 of the erection and 1/3 of the bracing credit, which compared well to estimating manual values and agreed with on-site observations of project data.

The PDCM procedures should be revised to collect more system factor data, including wall height and elevation changes. Also, critical dimensions and notes on complexity of bulkheads, boxouts, corbels, pilasters, and other complicating features should be recorded. Output quantities and workhours expended to construct bulkheads, boxouts, and blockouts should be tracked separately.

6.3 Recommendations for Future Research

Future research should focus on better defining and quantifying the critical productivity influence factors identified in this study. The PIF values presented here are recognized to be limited by the quantity of available data. The influence of footing elevation changes, piecework, and penetrations, for example, are not well established by other sources.

Base rates vary between projects based on various management and site factors. Determining the impact of these is critical to developing any formwork productivity forecasting factor model.

Material factors such as form maintenance, panel size, and form face material were touched upon in this thesis, but require further research to determine their precise impact. Steel forms seemed to be less efficient than plywood faced forms. Most of the projects used similar panel connection and bracing hardware, so it was difficult to draw any conclusions about their influence.

The relationship of occupied wall area, relative complexity, quantity, and location to the productivity influence of bulkheads, boxouts, and blockouts also requires additional research. One method would involve collection of separate productivity data for each item, such as workhours per 100 SFCA for bulkheads. An alternative approach would be the regression analysis described earlier.

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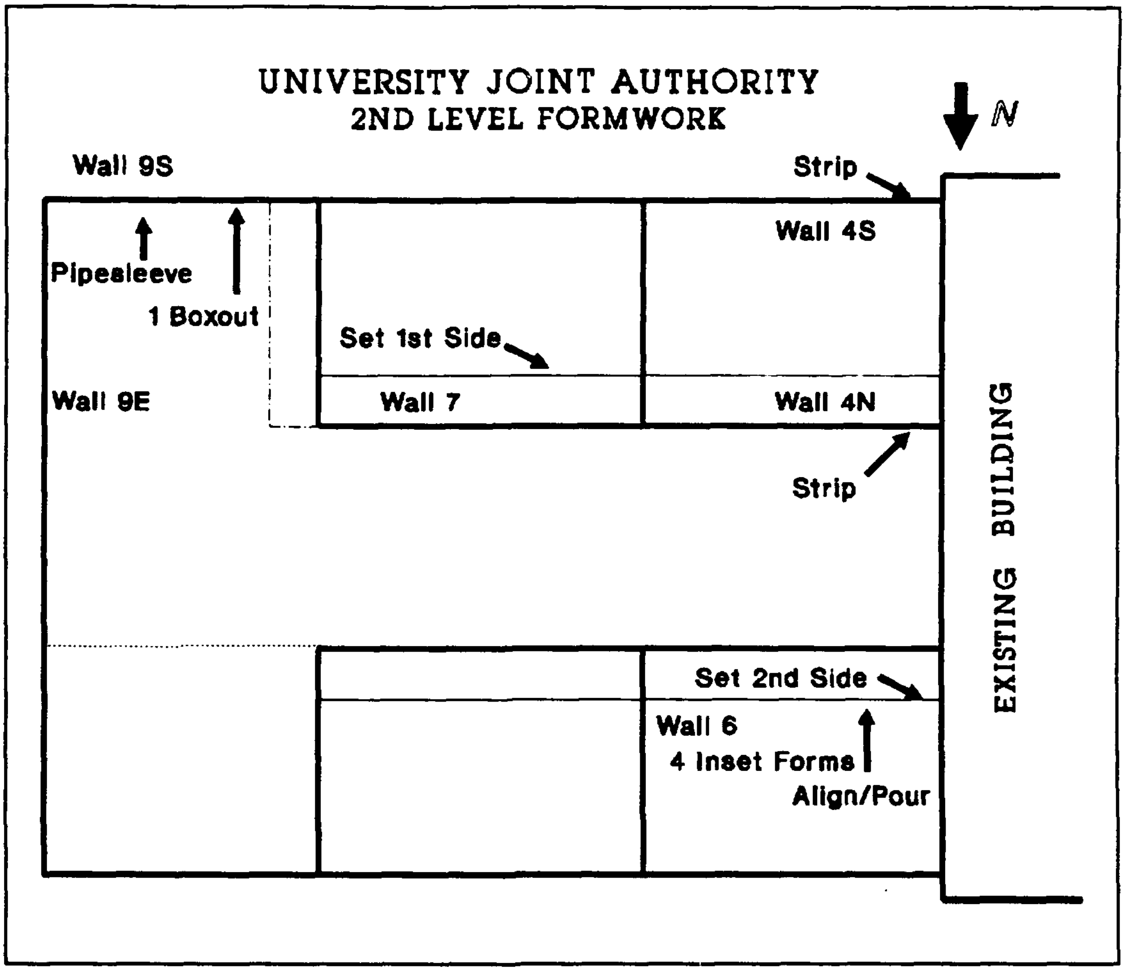
Appendix A

DATA COLLECTION FORMS



Date: August 15, 1991 Workday: 30 Length (hours): 9

Weather - Rain: T-Storms Temperature: 80 Comment: 1 Hour

Crew: 6 Carp./2 Labor Support Crew: 0 Foreman Hours: 4.5
Formwork Crew Workhours: 76.5 Support Hours: 0
Comments: Foreman also supervising pumpstation/pipe instal.

Daily Quantities (SFCA)
Fabricate/Pregang: 0 Avg. Height (Feet): 7.5
Erect 1st Side: 105 (Wall #7) Pilasters (SFCA): 0
Erect 2nd Side: 186 (Wall #6) Boxouts (# & SFCA): 5/ 25.5
Brace: 578 (Walls 6,7,9E) Pipesleeves (#/Diameter): 1/42"
Align: 372 (Wall 6-Pour) Bulkheads (# & SFCA): 0/ 0
Strip: 116 (Plywood #4N) Corners (# & Linear Ft.): 0/0

Panel Size: 2' x 8' Panel Type: Mod. Gang Forms (%): 0

Disruptions: Weather/Pipesleeve Comments: Pipe not Braced

Sample Daily Productivity Data Collection Worksheet

Table A.1 PDCM Data Collection Forms

Form No. Title [Frequency]		Form Items
1	Manpower/ Labor Pool [Daily]	Date, Workday, Productivity/Type Codes, Daily Workhours, Daily Quantities, Crew Size, Crew Compostion [Skilled/ Unskilled], Absenteeism, Labor Source.
2	Quantity Measurement [Daily for each prod./ type code]	Date, Workday, Subtask/Weight [Rules of credit] Erect 1st Side [SFCA], Erect 2nd Side, Align, Brace, Strip, Total Daily Quantity [SFCA - Sum of Subtask Quantities x Subtask Weights].
3	Design Features & Work Content [Daily]	Date, Workday, Work Type, Physical Elements, Design Details, Production vs. Piecemeal Work, Complexity Factor.
4	Environmental/ Site Conditions [Daily]	Date, Workday, Weather Conditions [Temperature and Humidity], Weather Severity Index.
5	Management Practices/ Control [Daily]	Date, Workday, Delay or Suspension [Duration and Cause], Organization of Storage Areas, Material Handling and Distribution, Materials Available, Tools Available, Interferences.
6	Construction Methods [Daily]	Date, Workday, Length of Workday [Duration/Cause], Production Goals, Incentive Schemes, Working Foreman, Construction Methods/Practices.
7	Project Organization [Daily]	Date, Workday, Labor Force, Number of Supervisors, Site Support Staff, Number of Foremen, Management Levels.
8	Project Features [Once]	Type of Project, Site Area, Floor Plan Area, Approximate Cost and Duration, Structural System, Stories, and Height.
9	Daily Diary [Daily]	Rework & Quality Control effects, Crane Availability, Interferences, Methods, Crew organization and Miscellaneous.

Source: Procedures Manual for Collecting Productivity and Related Data of Labor Intensive Activities on Commercial Construction Projects: Concrete Formwork (Thomas, Smith, and Horner 1991). [Productivity Data Collection Manual-PDCM]

Appendix B

PROJECT DATA

Table B.1 1st Level Tertiary Filter Bldg Productivity Data

		Quantities						Productivity	
Work Day	Work Hours	Erect Side1	Erect Side2	Brace	Align	Strip	Credit	Daily Rate	Cum. Rate
1	55.3	395	50	445			346	16.0	16.0
2	58.5	292	242	534			379	15.4	15.7
3	58.5		289	289	900		353	16.6	16.0
4	35.8		160	160	528		202	17.7	16.3
5	45.5	155		155		1290	253	18.0	16.5
6	49.5	192		192			154	32.2	18.0
7	49.5	297		297		138	251	19.7	18.2
8	49.5	92	276	368			239	20.7	18.5
9	35.8		92	92	736		202	17.7	18.4
10	44	368		368		138	30	14.3	17.9
11	49.5	253		253		598	262	18.9	18.0
12	49.5	144		144			115	43.0	19.0
13	49.5	144	265	306			254	19.5	19.0
14	41.3		103	206	736		230	18.0	18.9
15	31.5	138		138		736	184	17.1	18.8
16	40.5	109	247	356			235	17.2	18.7
17	33		161	60	494		179	18.4	18.7
18	49.5		234	315		402	197	25.2	19.0
19	55.3	14	207	221	736		283	19.6	19.1
20	35.8		204	204			122	29.2	19.3
21	58.5	77		77	230	414	149	39.3	19.9
22	58.5		234	234	454		231	25.3	20.2
23	24.8				620		124	20.0	20.2
24	24.8					1304	130	19.0	20.1
25	11.3					414	41	27.2	20.2

Work Type	Impacted Workdays	Remarks
Cleanup/Support	5, 24, 25	Strip/move components.

Disruption	Impacted Workdays	Remarks
Weather (Rain)	8, 21	Thunderstorms, moderate
Layout/Sequencing	12	Watertight door.

System Effect	Impacted Workdays	Remarks
Corners	1-5, 7, 11, 13-14,	Simple through Day 14.
	19, 22	More difficult.
Bulkheads	3, 4, 9, 13, 18	Similar/13.5 SFCA ea.
Difficult Penetration	6	42" pipesleeve.
or Boxout	20	Watertight door.
Pipesleeves	7, 11, 17, 18,	18-42" pipesleeves, L-
	19, 20, 22	shaped wall & northwall

Table B.2 2nd Level Tertiary Filter Bldg Productivity Data

Work Day	Work Hours	Quantities ** Erect Side1	Erect Side2	Brace	Align	Strip	Credit	Productivity Daily Rate	Cum. Rate
1	33.5	240		125			169	19.8	19.8
2	46	432		547			369	12.5	14.8
3	8		RAINOUT				0	----	16.3
4	40	392		359			307	13.0	15.1
5	20	50	111	194			113	17.7	15.4
6	7				231		46	15.2	15.4
7	2					111	11	18.0	15.4
8	25		PIPESLEEVE LAYOUT				0	----	17.9
9	40.5	80	126	103			119	34.0	19.6
10	54		432	421			257	21.0	19.8
11	58		349	423	822	120	401	14.5	18.6
12	33				1079		216	15.3	18.3
13	67.5	660		440		455	530	12.8	17.1
14	67.5	293	80	553		193	338	20.0	17.5
15	59.5	33	264	182		580	220	27.1	18.2
16	60		603	510	475		438	13.7	17.6
17	61		40	248	1418	314	381	16.0	17.4
18	94.5	795		545		986	685	13.8	16.9
19	94.5	356	52	738		907	473	20.0	17.2
20	94.5	40	611	651	626		524	18.0	17.3
21	84		490	490	1280		550	15.3	17.1
22	51	327		218	598	359	395	12.9	16.8
23	76.5	633		592		1018	600	12.8	16.5
24	76.5	464	186	800		413	554	13.8	16.3
25	65.5	33	663	561	372	1073	579	11.3	16.0
26	9					372	37	24.2	16.0
27	76.5		218	353	1255		409	18.7	16.1
28	58.5		352	352	1249		461	12.7	15.9
29	76.5	1057		770		902	878	8.7	15.3
30	76.5	105	186	578	372	116	339	22.6	15.6
31	68		502	336		784	346	19.6	15.7
32	76.5	81	556	803	1439	410	760	10.1	15.3
33	16.5				372		74	22.2	15.4
34	30				304	1036	164	18.3	15.4
35	48	390	186	576		768	500	9.6	15.2
36	37	316		316	372	975	425	8.7	14.9
37	48		537	537			322	14.9	14.9
38	32		22	22	1079	372	266	12.0	14.9
39	21					1079	108	19.5	14.9

** Modified for form fabrication using 2/3 of erect wall and 1/3 of brace wall rules of credit.

(Continued on next page)

Table B.2 (cont.) 2nd Level Tertiary Filter Bldg Productivity Data

Work Type	Impacted Workdays	Remarks
Fabricate/ Pregang Forms	1-2, 9-10, 14-16, 18-19	Major impact. Lesser influence.
Piecework	5-7	Low north corner wall.
Cleanup/Support	7, 34, 39	Strip/move components.

Disruption	Impacted Workdays	Remarks
Weather (Rain)	3, 26, 33 30	Stopped work early. 1 hour disruption.
Layout/Sequencing	8	Positioning of 3 pipe-sleeve penetrations.

System Effect	Impacted Workdays	Remarks
Wall Height (Most wall sections were 16.5-19.5 feet high)		
Lower walls	5-7, 24-25, 30, 32-33, 35	3.5' high corner wall and 7.5' baffle walls.
Gang-forming	1-2, 4, 10-11, 13-14, 16, 18, 22, 25, 28-29, 31, 35-36	Least efficient: Days 1, 10-11, 14 and 31. Most efficient: 35-36.
Corners	5, 10, 14-15, 17, 19, 20-21, 24-25, 27-28, 31-32, 35-37	Most complicated: Days 19-20 and 27-28. Easiest: Day 5.
Bulkheads	5, 8-9, 14-15, 31	Worst Impact: Days 8-9.
Large Pipesleeve	30-31	42" Dia., South wall.
Boxouts	10, 17, 19-20, 24, 27, 30-31, 34-35, 37	Most difficult: Day 31. Least difficult: Day 35.
Pipesleeves (Medium)	8-9, 14-15, 19-20, 24, 27	18-30" Pipesleeves, interior walls.
Pilasters	1, 22-23, 32	2.5' by 8", South Wall.
Rebar Templates	5, 15 31, 34, 37	Form rebar penetrations for wall continuation and slab intersections

Table B.3 Composting Facility Productivity Data

		Quantities						Productivity	
Work Day	Work Hours	Erect Side1	Erect Side2	Brace	Align	Strip	Credit	Daily Rate	Cum. Rate
1	96	2400		2400			1920	5.00	5.00
2	96		2018	2018	1642		1539	6.24	5.55
3	72		510	510	3286		963	7.48	5.97
4	111	2025	255	2280		2618	2035	5.46	5.81
5	111		930	930	2310	1155	1136	9.78	6.40
6	96	225	1185	1410	1155	1155	1238	7.76	6.59
07	88	1125	690	1815	1155	2310	1776	4.95	6.32
8	150	1740	1317	3057	2310	2310	2875	5.22	6.08
9	150	1560	1440	3000	2464	2310	2836	5.29	5.94
10	150	1470	1609	3079	2310	2464	2850	5.26	5.84
11	130	1230	1264	2494	2772	2310	2528	5.14	5.76
12	142	1575	1185	2760	2464	2772	2741	5.18	5.70
13	138	675	1635	2310	4620	2464	2691	5.13	5.64
14	138	1560	1215	2775	2310	2310	2670	5.17	5.60
15	150	1560	1504	3064	2464	2310	2874	5.22	5.56
16	150	1830	1594	3424	2464	2310	3144	4.77	5.49
17	150	1200	1756	2956	2772	2464	2814	5.33	5.48
18	81		632	632	2464	2464	1118	7.24	5.53
19	84	1125	945	2070		2772	1744	4.82	5.50
20	78		752	752	2310	2464	1160	6.73	5.54
21	68	1209		1209	2464	2310	1691	4.02	5.48
22	78		1269	1269	2478	2464	1503	5.19	5.47
23	16					2478	248	6.46	5.47

Work Type	Impacted Workdays	Remarks
Cleanup/Support	23	Strip/move components.

Disruption	Impacted Workdays	Remarks
Weather (Rain)	5, 18	Thunderstorms, Moderate

System Effect	Impacted Workdays	Remarks
Bulkheads [Quantity]	3, 6, 20, 22	Worst Impacted Days.
[Identical Design]	2, 4-5, 8-18	Less Impacted Days.
Step Forms	2-3, 5-6, 9-11, 17-18, 20, 22	Worst Impacted Days [Continued].
	4, 7-8, 12-16, 19	Less Impacted Days.

Table B.4 Art Museum Extension Productivity Data

		Quantities						Productivity	
Work Day	Work Hours	Erect Side1	Erect Side2	Brace	Align	Strip	Credit	Daily Rate	Cum. Rate
1	45	1297		961			970	4.6	4.6
2	45	1210		1418			1010	4.5	4.6
3	13.5	176		304			166	8.1	4.8
4	20	92		92			74	27.2	5.6
5	42.5		1680	1680			1008	4.2	5.1
6	12.5		250	250			150	8.3	5.3
7	30		783	783	1810		832	3.6	5.0
8	33.5				3678		736	4.6	4.9
9	14					1828	183	7.7	5.0
10	4	RAINOUT					---	----	5.1
11	20					3660	366	5.5	5.1
12	8	173		115			127	6.3	5.1
13	29	517	25	523	132		451	6.4	5.2
14	22.5	58	485	543			337	6.7	5.3
15	36	337	193	530	400	88	474	7.6	5.5
16	28	75	230	272	854		362	7.7	5.6
17	12				597		119	10.1	5.6
18	31	597		398		904	528	5.9	5.7
19	24	157		356		927	258	9.3	5.8
20	17	ERECT LARGE BOXOUTS					---	----	6.0
21	25		529	353			282	8.9	6.1
22	12		83	259	233		132	9.1	6.1
23	19.5		189	189	533		220	8.9	6.2
24	13.5				789		158	8.6	6.2
25	22	235		235		851	273	8.1	6.3
26	18		280	280		704	238	7.6	6.3
27	8				515		103	7.8	6.3
28	25	255	127	382		515	332	7.5	6.4
29	22	160	130	290	512		308	7.1	6.4
30	26	147	233	380		512	309	8.4	6.5
31	12		74	74	614		167	7.2	6.5
32	8					614	61	13.0	6.5
33	18	275	130	405			298	6.0	6.5
34	12		140	140	545		193	6.2	6.5
35	27.5	296	297	593		545	470	5.9	6.5
36	24	126	119	245	593		291	8.3	6.5
37	8				245	593	108	7.4	6.5
38	22	366	371	737	737	245	687	3.2	6.3
39	4					298	30	13.4	6.4
40	8	52	12	42	42	439	97	8.3	6.4
41	18	203	117	277	277		279	6.5	6.4
42	12	162	38	130	130	281	193	6.2	6.4
43	1					87	9	11.5	6.4

(Continued on next page)

Table B.4 (cont.) Art Museum Extension Productivity Data

Work Type	Impacted Workdays	Remarks
Piecework	12, 27, 37, 40	Less than 9 hours/day.
Cleanup/Support	9, 11, 32, 39, 43	Strip/move components.
Disruption	**Impacted Workdays**	**Remarks**
Weather (Rain)	10, 32, 39 36	Stopped work. 1 Hour Interruption.
System Effect	**Impacted Workdays**	**Remarks**
Wall Height (Avg.)		
8' - 16 '	1-3, 5-11, 13-17, 29-31	Work from ground/ little scaffolding.
16'- 26'	4, 18-24	Work off scaffolding.
Piers	13, 16, 40-42	Stand alone, 4.5-11'.
Columns	6, 12-16, 22, 34-36, 38	Adjoining wall section, various heights.
Bulkheads	3-4, 6, 25, 33-36	Most Difficult [high]. Less Difficult [low].
Corners	1, 3-7, 14-15, 19, 21-23 25-26, 28-29, 33-35, 38	Most Difficult [high]. Less Difficult [low].
Elevation Changes	4, 13-15, 25-26	Most difficult: 13-15.
Difficult Boxouts	4, 20	Large boxouts -Basement Walls (East & South).
Penetrations	30	5 small (<6" Dia.)
Other Boxouts	10, 19, 21-22, 26, 30	Utility boxouts for electrical/plumbing.
Column/Beam Benches	3, 4, 6, 8, 16-17 23-24, 27, 31, 34, 36-38	Largest impact: 8, 16. Least impact: 38.

Table B.5 Parking Deck Productivity Data

		Quantities **						Productivity	
Work Day	Work Hours	Erect Side1	Erect Side2	Brace	Align	Strip	Credit	Daily Rate	Cum. Rate
1	35	235	18	80			164	21.3	21.3
2	15	131	31	165	165		157	9.6	15.6
3	14	160		80		110	123	11.4	14.4
4	9	325					195	4.6	11.4
5	31	245	249	699	145		415	7.5	9.9
6	14	9	112	400	435		217	6.5	9.3
7	33		581	293	135		318	10.4	9.5
8	30		9	297	567	715	248	12.1	9.9
9	14				567		113	12.4	10.0
10	50	311	197	339		612	394	12.7	10.5
11	50	25	173	367	353		228	21.9	11.5
12	80	367	360	485	353	522	584	13.7	11.9
13	65			242	727		194	33.5	13.1
14	40	434		151			291	13.8	13.2
15	91	215	240	738	196	568	469	19.4	13.9
16	60		240	240	827	549	364	16.5	14.1
17	40	134	130	176		467	214	18.7	14.3
18	24		136	224			99	24.2	14.5
19	60	197	233	430		180	315	19.0	14.8
20	80	583	50	305			431	18.6	15.1
21	90	122	472	666	712		538	16.7	15.2
22	70	38	41	229	1024	414	331	21.1	15.5
23	15				400	130	93	16.1	15.6
24	48	204	37	150	150	764	274	17.5	15.6
25	24					811	81	29.6	15.8
26	60	345	336	606		693	532	11.3	15.5
27	65	348	336	759			495	13.1	15.3
28	76	194	120	314	1679		563	13.5	15.2
29	16					835	84	19.2	15.2
30	40	172	190	362		658	317	12.6	15.1
31	80	481	224	652		186	527	15.2	15.2
32	90	318	468	839			546	16.5	15.2
33	50				1853		371	13.5	15.2
34	42	106	65	171	171		158	26.6	15.3
35	10					506	51	19.8	15.4
36	8					363	36	22.0	15.4
37	100	615	545	773		555	797	12.6	15.2
38	95	351	290	1028	1267		786	12.1	15.0
39	75	171	146	348	881	1867	594	12.6	14.9
40	16					881	88	18.1	14.9

** Modified for form fabrication using 2/3 of erect wall and 1/3 of brace wall rules of credit. Only the three most impacted days were adjusted (workdays 1, 3, and 4).

(Continued on next page)

Table B.5 (cont.) Parking Deck Productivity Data

Work Type	Impacted Workdays	Remarks
Fabricate/ Pregang Forms	1, 3, 5, 11 9, 10, others	Major impact. Lesser influence.
Cleanup/ Support	25, 29, 35, 40 17, 18	Strip/move components. Erect scaffold/other.

Disruption	Impacted Workdays	Remarks
Weather (Rain)	15, 19, 21, 36	Not a large influence.
Layout/Sequencing	34	6' Long, 26' high wall piecework section. Cause: c-joint layout.
Rework	13	Corbel form error - found just before pour.

General Factor	Impacted Workdays	Remarks
Overtime	12 - 29	7 days/week, 10 hrs/day Worked on high walls.

System Effect	Impacted Workdays	Remarks
Wall Height (Avg.)		
8' - 16 '	1, 3, 5, 7-16, 30-33, 36-40	Some scaffolding/most work from ground.
16'- 26'	17-29, 34-35	Work off scaffolding.
Gang-forming	1, 3, 5, 7, 10-12, 14-16, 20, 26-27, 31, 37	Most effective: Days 26 and 27.
Piers	1-2, 24	Stand alone, 4.5-6.5'.
Columns	10-11, 14-15, 18-22, 24, 27, 30-31, 34, 37-39	Adjoining wall section, various heights.
Corners	4-6, 10-11, 18, 20, 39	L-shape most difficult.
Bulkheads	7-8, 11-13, 16, 20, 22, 27-28, 32-33, 37-39	Most difficult: Day 22. Easiest: 37-39.
Blockouts	7-9, 12, 19-20, 22-23, 28, 31-32, 34, 37-39	Used to form angled walls and ledges.
Corbels	11-12, 14-15, 17, 20, 26-27, 31-32, 34, 37	Largest impact 11-12. Least impact 34, 37.

Appendix C

PROJECT STATISTICAL ANALYSIS INFORMATION

Tertiary Filter Building, 1st Level

Base or "Undisrupted" Productivity Rate

From ANOVA:	16.20 workhours/100 SFCA
From Multiple Regression:	15.69 workhours/100 SFCA
Average:	15.95 workhours/100 SFCA

Disruption	ANOVA Mean Impacted Productivity Rate	PIF	Sig. Level
No Impact	20.08 wh/100 SFCA		0.0004
Weather	29.97 wh/100 SFCA	1.49	
Layout/Seq.	42.97 wh/100 SFCA	2.14	

Work Type from ANOVA

No Impact	16.20 wh/100 SFCA		0.0611
System Impacts	21.66 wh/100 SFCA	1.34	
Cleanup/ Support	21.02 wh/100 SFCA	1.29	

System Factors From ANOVA

No Impact	16.20 wh/100 SFCA		0.0001
Multiple	25.15 wh/100 SFCA	1.55	
Corners	16.46 wh/100 SFCA	1.02	
Bulkheads	17.87 wh/100 SFCA	1.10	
Pipesleeves			
Large	32.23 wh/100 SFCA	1.99	
Medium	20.37 wh/100 SFCA	1.26	
Boxouts	29.21 wh/100 SFCA	1.80	

System Factors Calculated from Multiple Regression

Constant	15.69 wh/100 SFCA		0.0000
Corners	16.53 wh/100 SFCA	1.05	0.4695
Bulkheads	17.44 wh/100 SFCA	1.11	0.0546
Pipesleeve	26.09 wh/100 SFCA	1.66	0.0002

Tertiary Filter Building, 2nd Level

Base or "Undisrupted" Productivity Rate

From ANOVA:	12.50 workhours/100 SFCA
From Multiple Regression:	12.28 workhours/100 SFCA
Average:	12.39 workhours/100 SFCA

Disruption	ANOVA Mean Impacted Productivity Rate	PIF	Sig. Level
No Impact	15.91 wh/100 SFCA		0.0000
Weather	22.98 wh/100 SFCA	1.44	
Spike	> 500 wh/100 SFCA	--	
Layout/Seq. Spike	> 500 wh/100 SFCA	--	
Repetition			
No Impact	16.73 wh/100 SFCA		0.2687
Repetitive	14.57 wh/100 SFCA	0.87	
Work Method			
Handset	17.94 wh/100 SFCA		0.0364
Gang Form	13.96 wh/100 SFCA	0.78	
Work Type from ANOVA			
No Impact	12.50 wh/100 SFCA		0.0000
System Impacts	19.14 wh/100 SFCA	1.53	
Piecework	16.52 wh/100 SFCA	1.32	
Cleanup/ Support	18.74 wh/100 SFCA	1.50	
System Factors From ANOVA			
No Impact	12.50 wh/100 SFCA		0.0001
Multiple	20.19 wh/100 SFCA	1.62	
Corners	13.09 wh/100 SFCA	1.05	
Bulkheads	14.75 wh/100 SFCA	1.18	
Boxouts	15.54 wh/100 SFCA	1.24	
Pipesleeves			
Large	19.63 wh/100 SFCA	1.57	
Medium	17.00 wh/100 SFCA	1.36	
Pilasters	13.88 wh/100 SFCA	1.17	
System Factors Calculated from Multiple Regression			
Constant	12.28 wh/100 SFCA		0.0000
Corners	12.49 wh/100 SFCA	1.02	0.8143
Bulkheads	15.60 wh/100 SFCA	1.27	0.0232
Pipesleeve	17.00 wh/100 SFCA	1.38	0.0000
Boxouts	14.52 wh/100 SFCA	1.18	0.0404
Rebar Temp.	13.08 wh/100 SFCA	1.07	0.6805
Pilasters	14.68 wh/100 SFCA	1.20	0.0223

Composting Facility

Base or "Undisrupted" Productivity Rate

From ANOVA:	4.70 workhours/100 SFCA
From Multiple Regression:	4.43 workhours/100 SFCA
Average:	4.57 workhours/100 SFCA

Disruption	ANOVA Mean Impacted Productivity Rate	PIF	Sig. Level
No Impact	5.51 wh/100 SFCA		0.0004
Weather	8.51 wh/100 SFCA	1.54	
Repetition			
No Impact	6.19 wh/100 SFCA		0.0006
Repetitive	5.16 wh/100 SFCA	0.83	
Work Type from ANOVA			
No Impact	4.70 wh/100 SFCA		0.1717
System Impacts	5.98 wh/100 SFCA	1.27	
Cleanup/ Support	6.46 wh/100 SFCA	1.37	
System Factors Calculated from Multiple Regression			
Constant	4.43 wh/100 SFCA		0.0000
Bulkheads	4.61 wh/100 SFCA	1.04	0.1475
Form Size Step Forms	4.83 wh/100 SFCA	1.09	0.1201

Art Museum Extension

Base or "Undisrupted" Productivity Rate

From ANOVA:	4.03 workhours/100 SFCA
From Multiple Regression:	4.63 workhours/100 SFCA
Average:	4.33 workhours/100 SFCA

Disruption	ANOVA Mean Impacted Productivity Rate	PIF	Sig. Level
No Impact	7.61 wh/100 SFCA		0.0003
Weather	11.57 wh/100 SFCA	1.52	
Spike	>500		
System Rel. Spike	>500		

Wall Height

Base [<8']	6.35 wh/100 SFCA		0.240
8'-16'	6.61 wh/100 SFCA	1.04	
Over 16'	11.11 wh/100 SFCA	1.75	

Work Type from ANOVA

No Impact	4.03 wh/100 SFCA		0.0713
System Impacts	7.66 wh/100 SFCA	1.90	
Piecework	7.44 wh/100 SFCA	1.85	
Cleanup/ Support	8.20 wh/100 SFCA	2.03	

System Factors From ANOVA

No Impact	4.03 wh/100 SFCA		0.2631
Multiple	11.08 wh/100 SFCA	2.75	
Corners	6.36 wh/100 SFCA	1.58	
Elev. Changes	6.65 wh/100 SFCA	1.65	
Bulkheads	6.89 wh/100 SFCA	1.71	
Boxouts	7.70 wh/100 SFCA	1.91	
Column/ Beam Seats	6.77 wh/100 SFCA	1.68	

Parking Deck

Base or "Undisrupted" Productivity Rate

From ANOVA:	---- workhours/100 SFCA
From Multiple Regression:	9.74 workhours/100 SFCA
Average:	9.74 workhours/100 SFCA

Disruption	ANOVA Mean Impacted Productivity Rate	PIF	Sig. Level
No Impact	15.00 wh/100 SFCA		0.0001
Weather	19.31 wh/100 SFCA	1.29	
Layout/Seq.	26.58 wh/100 SFCA	1.77	
Rework	33.54 wh/100 SFCA	2.24	

Repetition

No Impact	15.64 wh/100 SFCA		0.0006
Repetitive	13.61 wh/100 SFCA	0.87	

Work Method

Handset	14.44 wh/100 SFCA		0.4898
Gang Form	13.20 wh/100 SFCA	0.91	

Overtime

8-16' High Walls			0.0004
No Overtime	13.70 wh/100 SFCA		
Overtime	14.64 wh/100 SFCA	1.07	

Wall Height

Base [<8']	7.02 wh/100 SFCA		0.0004
8'-16'	13.70 wh/100 SFCA	1.95	
Over 16'	17.13 wh/100 SFCA	2.44	

Work Type from ANOVA

General	13.95 wh/100 SFCA		0.0001
Cleanup/ Support	19.90 wh/100 SFCA	1.29	

System Factors From ANOVA

No Impact	9.74 wh/100 SFCA		0.0077
Overall	13.38 wh/100 SFCA	1.37	
Multiple	15.44 wh/100 SFCA	1.59	
Corners	13.26 wh/100 SFCA	1.36	
Bulkheads	14.98 wh/100 SFCA	1.54	
Blockouts	12.74 wh/100 SFCA	1.31	
Corbels	12.91 wh/100 SFCA	1.33	

System Factors Calculated from Multiple Regression

Constant	9.74 wh/100 SFCA		0.0000
Corners	11.49 wh/100 SFCA	1.18	0.2295
Bulkheads	12.01 wh/100 SFCA	1.23	0.0459
Blockouts	11.18 wh/100 SFCA	1.15	0.1311
Rebar Temp.	12.06 wh/100 SFCA	1.24	0.5033
Corbels	11.29 wh/100 SFCA	1.16	0.1992